

**GUGGENHEIM AERONAUTICAL LABORATORY**

**CALIFORNIA INSTITUTE OF TECHNOLOGY**

PERFORMANCE CALCULATIONS OF ROCKET TRIPROPELLANT SYSTEMS

Thesis by

Lieutenant Commander William E. Sims, U. S. Navy

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ROCKET TRIPROPELLANT SYSTEMS

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LIEUTENANT COMMANDER WILLIAM E. SIMS, U. S. NAVY

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## ABSTRACT

This investigation was conducted to determine the effect on performance and temperatures of the addition of either liquid hydrogen or liquid ammonia to three bipropellant systems of current interest. These bipropellant systems are nitrogen tetroxide-hydrazine, hydrogen peroxide-hydrazine, and RFNA-hydrazine.

For each tripropellant system all important parameters and chamber and exhaust temperatures are determined for equilibrium flow conditions and constant composition flow conditions. All the results are listed in tables and the effects on several of the more important parameters are illustrated graphically.

The results show that theoretically the effect of the addition of the third component is desirable by causing reduction in temperature and increase in performance.

New parameters were introduced for utilization in predicting performances of tripropellant systems once the chamber temperature has been calculated or estimated.

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## INTRODUCTION

One of the major problems in the operation of thermal jet and rocket engines is the reduction in heat transfer to the combustion chamber walls. One solution to the problem of maintaining the wall material below its melting point has been the use of exterior cooling systems to maintain the temperature of the wall considerably below the temperature of the gas. To recover part of the heat lost in this manner the fuel or oxidant may be used as the exterior coolant. Such a system is said to be regeneratively cooled. For high performing propellant systems excessively high temperatures are encountered in the combustion chamber and the convergent section of the nozzle; therefore, it is necessary to resort to more effective methods of cooling (Cf. Ref. 1). Furthermore, many of the newer fuels and oxidants are so unstable that it is not possible to use them in regeneratively cooled systems.

Theoretically at all operating temperatures, and practically, at least at lower temperatures, it has been shown that film or transpiration cooling techniques offer certain operative advantages (Cf. Ref. 2). In addition, such techniques theoretically appear to lend themselves to application to very hot propellant systems operating over longer periods of time.

In film or transpiration cooling, the coolant moves in counterflow to the heat flow through the wall material,

and evaporates on the surface exposed to the high temperature, and may or may not take part in the combustion on entering the combustion zone in the chamber. The extent of the mixing with the combustion gases is not yet known nor is it known what efficiency of absorption of radiant energy by a gas or vapor stream may be expected.

The addition of a third component as film or transpiration coolant to the combustion reaction, if properly chosen, may have certain desirable effects on the calculated performances and the adiabatic flame temperatures, assuming adequate mixing and complete chemical reaction. The extent to which these assumptions identify the actual conditions of operation will have to be determined experimentally. The theoretical effect on performance and gas temperature of combustion is of immediate interest since it will indicate the direction and order of magnitude (Cf. Ref. 3) of the change in performance parameters to be expected.

Hydrogen (liquid or gas) and ammonia (liquid or gas) have previously been demonstrated (Cf. Refs. 3, 4, 6, and 7) to be the most effective third components to be added to present propellant systems, although water (liquid) has been considered seriously (Cf. Refs. 7 and 8). These components or their dissociation products lower the chamber temperature by decreasing the available energy per pound of total propellant and increase the performance, both very desirable effects. Increased performance is possible because of the lower average molecular weight of the products

of reaction resulting from the addition of the third component.

For these reasons, the investigation of the effect of the addition of a third component on the performance of rocket propellant systems currently of interest was undertaken. These systems of immediate interest were: RFNA-hydrazine system with liquid ammonia added, RFNA-hydrazine with liquid hydrogen added, nitrogen tetroxide-hydrazine with liquid ammonia added, nitrogen tetroxide-hydrazine with liquid hydrogen added, hydrogen peroxide-hydrazine with liquid ammonia added, and hydrogen peroxide-hydrazine with liquid hydrogen added. A re-evaluation of the performance in stoichiometric proportion of the hydrogen peroxide-hydrazine system was also undertaken since earlier calculations (Cf. Ref. 8) neglected molecular and atomic oxygen in the mass and heat balances.

The performance parameters were evaluated for each tripropellant system at a mixture ratio corresponding to stoichiometric proportions with respect to the bipropellant oxidant and fuel, but with varying amount of third component (liquid hydrogen or ammonia) added in excess. Stoichiometric proportions were chosen since the chamber temperature ( $T_c$ ) was very nearly a maximum at this mixture ratio (the real maximum is slightly on the reductant-rich side of stoichiometric) and the reduction in flame temperature by an addition would be most marked.

# EXPLANATION OF SYMBOLS

a	Number of moles of water vapor ( $H_2O$ ) in the products of reaction
b	Number of moles of hydrogen ( $H_2$ ) in the products of reaction
c	Number of moles of hydroxyl ions (OH) in the products of reaction
d	Number of moles of atomic hydrogen (H) in the products of reaction
e	Number of moles of oxygen ( $O_2$ ) in the products of reaction
f	Number of moles of atomic oxygen (O) in the products of reaction
g	Number of moles of nitrous oxide (NO) in the products of reaction
h	Number of moles of nitrogen ( $N_2$ ) in the products of reaction
H	Number of gram atoms of hydrogen in the reactants
N	Number of gram atoms of nitrogen in the reactants
O	Number of gram atoms of oxygen in the reactants
$a_c$	Velocity of sound corresponding to chamber conditions ( $ft\ sec^{-1}$ )
c	Effective exhaust velocity ( $ft\ sec^{-1}$ )

$c^*$	Characteristic velocity (ft sec <sup>-1</sup> )
$C_F$	Theoretical thrust coefficient of nozzle
$(C_p)_c$	Apparent molar isobaric heat capacity of products of reaction at equilibrium chamber temperature (cal mol <sup>-1</sup> °K <sup>-1</sup> )
$(C_v)_c$	Apparent molar isochoric heat capacity of products of reaction at equilibrium chamber temperature (cal mol <sup>-1</sup> °K <sup>-1</sup> )
$\bar{C}_p$	Average apparent molar isobaric heat capacity of products of reaction during their passage through nozzle (cal mol <sup>-1</sup> °K <sup>-1</sup> )
$\bar{C}_v$	Average apparent molar isochoric heat capacity of products of reaction during their passage through nozzle (cal mol <sup>-1</sup> °K <sup>-1</sup> )
$E(I_{sp})$	Dimensionless parameter equal to $\frac{I_{sp}^o}{I_{sp}} - \frac{T_c^o}{T_c}$
$E(h)$	Dimensionless parameter equal to $\frac{h}{h^o} - \frac{T_c}{T_c^o}$
$f_t$	Nozzle throat area (sq in)
$F$	Thrust of rocket motor (lb)
$g$	Acceleration of gravity (arbitrarily chosen equal to 32.2 ft sec <sup>-2</sup> )
$h$	Altitude index (mi)



$\Delta H_{300}^T$ ,  $\Delta H_{T_e}^T$ , etc. Change in enthalpy of the products of reaction (k cal) between superscript temperature ( $^{\circ}\text{K}$ ) and subscript temperature ( $^{\circ}\text{K}$ )

$\int H_{T_1}^{T_2}$  Enthalpy change in a specified system from  $T_1$  to  $T_2$  with the system in chemical equilibrium (k cal)

$I_{sp}$  Specific impulse of propellant (sec)

$J$  Mechanical equivalent of heat  
( $4.186 \times 10^{10}$  ergs k cal $^{-1}$ )

$K_1, K_2$ , etc. Equilibrium constants expressed in terms of partial pressures for particular reactions as listed on page 47

$K_{n_1}, K_{n_2}$ , etc. Equilibrium constants expressed in terms of number of moles of components for particular reactions as listed on page 47

$m$  Total weight of reactants (gm)

$\dot{m}$  Weight rate of flow through nozzle  
(lb sec $^{-1}$ )

$\bar{M}$  Average molecular weight of the products of reaction during their passage through the nozzle

$\bar{M}_c$  Average molecular weight of the products of reaction at equilibrium chamber temperature

$n_p$  Number of moles of products of reaction



$\bar{n}_p$	Average number of moles of products of reaction present during their passage through the nozzle
$n^{T_c}, n^{2000}, \text{etc.}$	Number of moles at temperature ( $^{\circ}\text{K}$ ) indicated by superscript
$\Delta n_1, \Delta n_2, \text{etc.}$	Number of moles of products minus the number of moles of reactants indicated in balanced equilibrium equation for a particular reaction
$P$	Total pressure of the products of reaction (atm.)
$P_e$	Nozzle exhaust pressure (psia)
$P_c$	Chamber pressure (psia)
$Q_{av}^{T_c}, Q_{av}^{2500}, \text{etc.}$	Heat available from completion of reaction at temperature ( $^{\circ}\text{K}$ ) as indicated by superscript (k cal)
$\Delta Q_{av} \frac{T_c}{T_e}$	Change in heat available between $T_c$ and $T_e$ (k cal)
$Q_f$ (reactants)	Heat of formation of the reactants at $300^{\circ}\text{K}$ (k cal)
$Q_f$ (products)	Heat of formation of the products at $300^{\circ}\text{K}$ (k cal)
RFNA	Red fuming nitric acid (in this investigation, nitric acid with 6.8% by weight $\text{N}_2\text{O}_4$ )
$R_u$	Universal gas constant (1.986 cal $\text{mol}^{-1} \text{ } ^{\circ}\text{K}^{-1}$ , $8.315 \times 10^7$ ergs $\text{mol}^{-1} \text{ } ^{\circ}\text{K}^{-1}$ )

$T$	Absolute temperature ( $^{\circ}\text{K}$ )
$T_c$	Equilibrium chamber temperature ( $^{\circ}\text{K}$ )
$T_e$	Exhaust temperature ( $^{\circ}\text{K}$ )
$\bar{\rho}$	Average density of rocket propellant ( $\text{gm cm}^{-3}$ )
$\gamma$	Ratio of isobaric to isochoric heat capacity ( $C_p/C_v$ )
$\gamma_c$	Ratio of apparent isobaric to isochoric heat capacity of products of reaction at equilibrium chamber temperature
$\bar{\gamma}$	Ratio of average apparent isobaric to isochoric heat capacity of the pro- ducts of reaction during their passage through the nozzle
$\Gamma'$	A function of $\gamma$ defined by $\Gamma' = \gamma \left( \frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}}$
$\Gamma'_{(\gamma_c)}$	$\Gamma'$ evaluated for $\gamma = \gamma_c$
$T_c^0, I_{sp}^0, h_a^0$ , etc.	Superscript zero indicates value of parameter for bipropellant system at stoichiometric mixture ratio

## PART I

### DISCUSSION OF ASSUMPTIONS AND INTRODUCTION OF PARAMETERS

The assumptions used in evaluating the theoretical performances of the tripropellant systems were that

1. The propellants react completely and there is sufficient time for the establishment of equilibrium concentrations of the normally unexcited components -  $H_2$ ,  $H_2O$ ,  $NO$ ,  $N_2$ ,  $N$ ,  $O_2$ ,  $O$ ,  $H$ ,  $OH$  - at the adiabatic flame temperature determined by the mass and heat balance. All minor components are considered in these calculations except atomic nitrogen ( $N$ ).
2. The equipartition of energy among the electronic, vibrational, and rotational energy levels is assumed to be instantaneous, both in the chamber and in the expansion process, for constant composition and equilibrium flow conditions assumed.
3. Over a temperature range of 100 degrees,  $Q_{av}$ ,  $\Delta H^T_{300}$ , and gas mixture composition versus temperature are assumed to be linear.
4. Chamber pressure ( $P_c$ ) is 300 psia for all calculations presented herein, and the exhaust pressure ( $P_e$ ) is assumed to be 14.7 psia.

5. For constant composition flow calculations, the propellant gas composition remains constant and equal to the composition at the adiabatic flame temperature in the chamber ( $T_c$ ).
6. For equilibrium flow calculations the composition of the products changes continuously with pressure and temperature along the nozzle and the energy released in shifting the equilibrium involved is made available for increased performance.
7. Steady flow prevails throughout the nozzle. That is; shock disturbances are neglected, velocity profile is uniform and flat, compressibility and viscous effects are neglected. It is further assumed one dimensional equations are valid.
8. The expansion process is isentropic and the combustion takes place adiabatically.
9. The enthalpy of the reaction products is independent of the pressure since relatively low pressures were used in these calculations.
10. Velocity of the reaction products in the chamber is negligible compared to effective exhaust velocity.
11. In computing the characteristic velocity ( $c^*$ ) the ratio of specific heats ( $\gamma$ ) is assumed to be the ratio of the specific heats at the

equilibrium chamber temperature, and equal to  $\gamma_c$ . The  $\gamma_c$  is based on the change of enthalpy over the one hundred degree interval nearest the chamber temperature ( $T_c$ ) at a constant pressure equal to the chamber pressure. For the expansion process a constant average isobaric heat capacity ( $C_p$ ) is assumed.

The foregoing assumptions were used in calculating the parameters necessary to compare the systems and the effect of adding a third component. Since achieving a high terminal velocity is essential, the impulse is a more significant parameter than the energy dissipated. Consequently, the specific impulse which is the thrust per unit weight rate of flow is computed and is the ratio of the effective exhaust velocity to the acceleration of gravity. This is one of the most useful parameters in comparing propellant systems.

Effective exhaust velocity is of equal importance as a parameter since it is indicative of momentum change ( $c = I_{sp} g$ ). The effective exhaust velocity is the nozzle exit velocity (axial) and is also defined as the ratio of the thrust to mass rate of flow. Thus, it is easily calculated both experimentally and theoretically.

The characteristic velocity ( $c^*$ ) parameter is computed since it is determined only by the properties of the propellant and the throat diameter and is independent of the exit conditions. It is a measure of the combustion efficiency

and readily calculated considering only the propellant properties ( $T_c$ ,  $\gamma_c$ ,  $\bar{M}_c$ ) at the combustion conditions. In this way it is very useful to obtain quick estimates of the merit of a propellant system.

The nozzle thrust coefficient ( $C_F$ ) has been found to be a useful parameter. It is a function of chamber pressure, nozzle throat area, and the thrust developed. Theoretically, it may be evaluated from the ratio of the effective exhaust velocity to the characteristic velocity.

The altitude index is a useful parameter in comparing propellant systems since it is a weighted function of specific impulse and propellant density. It is a comparison of the altitude attainable by an arbitrarily chosen large total impulse rocket with a rocket of specified total impulse. By using a large rocket the propellants become only functions of their specific impulse and density and thus provide a good measure of their relative merit for long range or high altitude missile application.

The values of altitude index were based on equations for bipropellant systems and, therefore, produce values that are slightly optimistic.





## PART II

### DEVELOPMENT OF THE EQUATIONS FOR SOLVING THE COMPOSITION OF THE PRODUCTS OF REACTION INCLUDING MINOR COMPONENTS

The equations developed here for determining the composition of the products of reaction are of necessity synonymous to methods previously developed for solving similar problems. They represent an independent derivation, however. As a result, the use and nomenclature of the equations are slightly different.

Although there have been numerous methods of solution for this type problem, they are all time consuming and laborious. Several methods were investigated in an effort to find a quick exact solution, but the final conclusion was that some methods, although of equal adaptability, did not offer any definite advantage over the method used in this thesis, either in time or accuracy.

The products of reaction of all the propellant systems investigated contained  $H_2$ ,  $H$ ,  $OH$ ,  $NO$ ,  $N_2$ ,  $H_2O$ ,  $O$ ,  $O_2$ . The following system of symbols was used to represent the atomic and molecular species present in the combustion gases:

- a = number of moles of water vapor ( $H_2O$ )
- b = number of moles of hydrogen ( $H_2$ )
- c = number of moles of hydroxyl ion ( $OH$ )
- d = number of moles of atomic hydrogen ( $H$ )
- e = number of moles of oxygen ( $O_2$ )
- f = number of moles of atomic oxygen ( $O$ )

$g$  = number of moles of nitrous oxide (NO)

$h$  = number of moles of nitrogen ( $N_2$ )

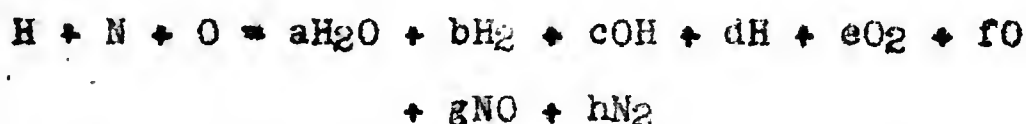
$H$  = number of gram atoms of hydrogen

$N$  = number of gram atoms of nitrogen

$O$  = number of gram atoms of oxygen

The major components are molecular hydrogen, molecular nitrogen, and water vapor. The minor components are atomic hydrogen, nitrous oxide, atomic oxygen, oxygen, atomic nitrogen, and the hydroxyl ion. The presence of atomic nitrogen is neglected in this investigation.

Therefore, the problem is to find at least eight equations by the use of which the eight unknowns can be solved. The reaction equation for systems containing hydrogen, nitrogen, and oxygen is:



This immediately gives three of the necessary eight equations by setting up the atom balances:

$$\text{Sum of hydrogen atoms:} \quad H = 2a + 2b + c + d \quad (1)$$

$$\text{Sum of oxygen atoms:} \quad O = a + c + 2e + f + g \quad (2)$$

$$\text{Sum of nitrogen atoms:} \quad N = g + 2h \quad (3)$$

The remaining five equations were obtained by considering reactions and dissociations among the eight products of reaction. Equilibrium must be assumed and the resulting equations are as follows:



$$K_{n3} = \frac{g \cdot b}{h \cdot 5a} \quad (4)$$

$$2\text{H}_2\text{O} = \text{O}_2 + 2\text{H}_2 \quad (\Delta n_6 = 1.0)$$

$$K_{n6} = \frac{eb^2}{a^2} \quad (5)$$

$$\text{H}_2\text{O} = \text{O} + \text{H}_2 \quad (\Delta n_7 = 1.0)$$

$$K_{n7} = \frac{fb}{a} \quad (6)$$

$$\frac{1}{2}\text{H}_2 = \text{H} \quad (\Delta n_9 = 0.5)$$

$$K_{n9} = \frac{d}{b \cdot 5} \quad (7)$$

$$\text{H}_2\text{O} = \text{OH} + \frac{1}{2}\text{H}_2 \quad (\Delta n_{10} = 0.5)$$

$$K_{n10} = \frac{cb \cdot 5}{a} \quad (8)$$

The tabular values of the equilibrium constants used from Table I were based on ratios of partial pressures, but since the development here depends on the moles of gases it was necessary to convert the  $K_3$ ,  $K_6$ ,  $K_7$ ,  $K_9$ , and  $K_{10}$  to  $K_{n3}$ ,  $K_{n6}$ ,  $K_{n7}$ ,  $K_{n9}$ , and  $K_{n10}$  by the following general relation:

$$K_n = K \left( \frac{n_p}{P} \right)^{(\Delta n)} \quad (9)$$

where  $n_p$  = number of moles of products of reaction

$P$  = total pressure of products of reaction

$\Delta n$  = number of moles of products minus the number of moles of reactants obtained from balanced equilibrium equation

Also, there is an additional equation since  $K_n$  is a function of total moles of products of reaction where

$$n_p = a + b + c + d + e + f + g + h \quad (10)$$

It is pointed out that  $n_p$  must also be estimated for each particular solution.

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These equations can be solved to express the composition of each of the components as a function of, at the most, two unknowns, giving the following equations:

$$a = \frac{H b^{.5} - K_{n9} b - 2 b^{1.5}}{2 b^{.5} + K_{n10}} \quad (11)$$

$$b = b \quad (\text{where } b = \text{assumed trial value}) \quad (12)$$

$$c = \frac{K_{n10} a}{b^{.5}} \quad (13)$$

$$d = K_{n9} b^{.5} \quad (14)$$

$$e = \frac{K_{n6} a^2}{b^2} \quad (15)$$

$$f = \frac{K_{n7} a}{b} \quad (16)$$

$$g = 0 - a - c - 2e - f \quad (17)$$

$$h = \frac{1}{2} (N - g) \quad (18)$$

$$n_p = a + b + c + d + e + f + g + h \quad (19)$$

$$K_{n3} = \frac{g b}{a h^{.5}} \quad (20)$$

With these equations all the unknown quantities can be found if the correct estimate of "b" can be found. The correct value of "b" is found by trial and error. Therefore, the following trial and error procedure is employed.

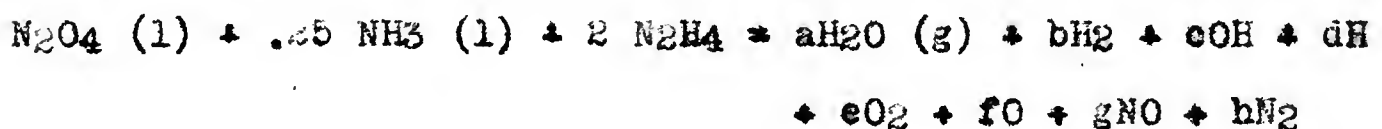
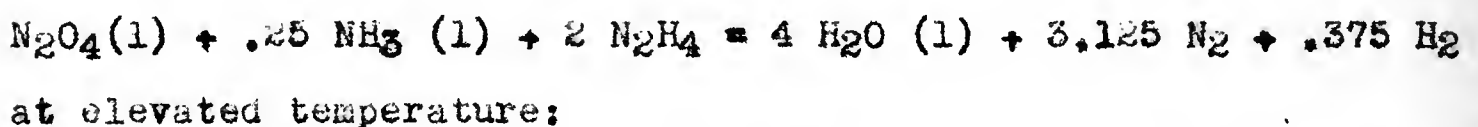
1. Estimate  $T_c$  to nearest  $100^\circ \text{ K}$ .
2. Estimate  $n_p$  and compute the equilibrium constants ( $K_n$ 's) for total pressure of products of reaction for this estimated  $T_c$ .
3. Estimate "b", number of moles of hydrogen.

4. Calculate other components from this estimated "b", using Equations (11) through (18).
5. From Equation (19), find  $n_p$ . Compare with estimated  $n_p$  of Step 2.
6. From Equation (20), find  $K_{N_2}$ . Compare this with  $K_{N_2}$  of Step 2. These two will be identical if  $n_p$  estimated =  $n_p$  actual.
7. Repeat calculations based on new value of "b" until agreement of  $n_p$  (estimated) =  $n_p$  (computed) and  $K_{N_2}$  (Step 6) =  $K_{N_2}$  (Step 2).
8. As a check on numerical accuracy, Equations (1), (2), and (3) should be used.

To demonstrate the use of these equations for determining the composition of the products of reaction, the following sample calculation is presented.

The composition is to be solved for a particular temperature and pressure corresponding to chamber conditions in a rocket motor. The propellant system chosen to best demonstrate the use of these equations is nitrogen tetroxide and hydrazine at stoichiometric with the addition of  $\frac{1}{4}$  mole of liquid ammonia.

The chemical equation expressing the reaction of the propellant is given, at low temperature, as:



From this equation,  $n_p$  is found to be equal to or greater than 7.5 moles.

Using equations (1), (2), and (3), the following three equations are obtained:

Sum of hydrogen atoms

$$H = 8.75 = 2a + 2b + c + d$$

Sum of oxygen atoms

$$O = 4.0 = a + c + 2e + f + g$$

Sum of nitrogen atoms

$$N = 6.25 = g + 2h$$

Now employing Equations (11) through (18), an additional seven equations are obtained:

$$a = \frac{8.75 b^{.5} - K_{n9} b - 2b^{1.5}}{2 b^{.5} + K_{n10}}$$

$$b = b$$

$$c = \frac{K_{n10} a}{b^{.5}}$$

$$d = K_{n9} b^{.5}$$

$$e = \frac{K_{n6} a^2}{b^2}$$

$$f = \frac{K_{n7} a}{b}$$

$$g = 4.0 - a - c - 2e - f$$

$$h = \frac{1}{2}(6.25 - g) = 3.125 - g/2$$

It was now necessary to choose a temperature to the nearest  $100^\circ \text{K}$  and to estimate the total number of moles of all the reactants at this temperature.

With  $T = 3200^\circ \text{ K}$ ;  $P_c = 300 \text{ psia}$ ;  $n_p = 7.8 \text{ moles}$ ,  
the composition was computed.

$T$	$3200^\circ \text{ K}$
$n_p$	7.8
$(n_p/P) (\Delta n=1)$	0.382
$(n_p/P) (\Delta n=0.5)$	0.618
$K_{n3}$	0.00800
$K_{n6}$	0.00270
$K_{n7}$	0.00727
$K_{n9}$	0.1738
$K_{n10}$	0.0672

To begin the trial and error solution of the composition, a representative value of "b" was chosen.

In the first trial, "b" was taken equal to 0.7 moles,  
and the equations (11) through (18) solve:

a	3.463
b	0.700
c	0.278
d	0.145
e	0.066
f	0.036
g	0.091
h	3.080
$K_{n3} \text{ (calculated)}$	0.008
$n_p$	7.859



Comparing  $K_{n3}$  and  $n_p$  calculated with  $K_{n3}$  and  $n_p$  based on assumptions, it was found that

$$K_{n3} \text{ (based on assumed values)} = 0.00800$$

compared with

$$K_{n3} \text{ (calculated)} = 0.00800$$

and

$$n_p \text{ (assumed)} = 7.80$$

compared with

$$n_p \text{ (calculated)} = 7.859$$

With this information, it was necessary to assume another  $n_p = 7.86$ , and resolve the equations with an adjusted value of "b" = 0.690.

T	3200
$n_p$	7.86
$(n_p/P) (\Delta n=1.0)$	0.385
$(n_p/P) (\Delta n=0.5)$	0.620
$K_{n3}$	0.00802
$K_{n6}$	0.00272
$K_{n7}$	0.00733
$K_{n9}$	0.1743
$K_{n10}$	0.0674
a	3.473
b	0.0690
c	0.282
d	0.145
e	0.069
f	0.037

g	0.070
h	3.090
$K_{N_2}$	0.00802
$n_p$	7.856

Comparing results of second trial showed  $K_{N_2}$ 's to be in exact agreement and  $n_p$  calculated = 7.856 compared to  $n_p$  estimated = 7.860. This difference is negligible. Therefore, the exact composition is computed for the chosen temperature,  $T = 3200^\circ \text{K}$ , at a pressure,  $P = 300 \text{ psia}$  (20.41 atms.).

### PART III

#### SAMPLE CALCULATIONS OF PERFORMANCE PARAMETERS

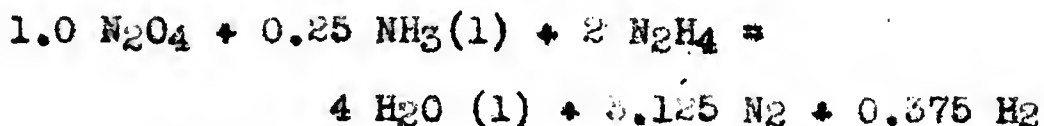
Calculations are made on the nitrogen tetroxide (liquid) and hydrazine (liquid) propellant system at stoichiometric with the addition of  $\frac{1}{4}$  mole of liquid ammonia as the third component to illustrate the methods presented thus far.

Since a sample calculation for the determination of the propellant composition at a chosen temperature has been made in Part II, these calculations will proceed from that point in order to avoid duplication.

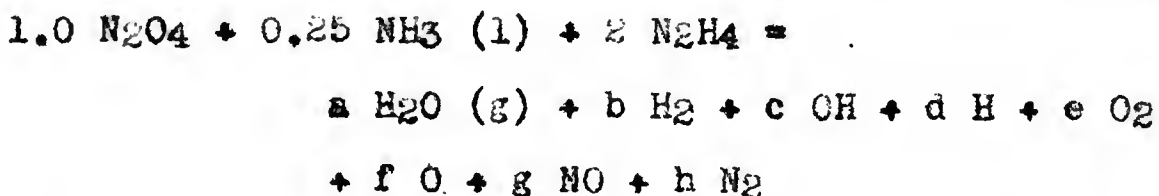
The chemical equation at stoichiometric mixture of this propellant system is at low temperature:



With the addition of  $\frac{1}{4}$  mole of liquid ammonia to the above equation, it became:



At an elevated temperature the chemical equation is:



Total mass of all products of reaction is equal to 160.32 gms.

Step A. Calculation of Chamber Temperature ( $T_c$ )

Estimate  $T_c$  to the nearest  $100^\circ$  K. Choose  $T_c$  (est.) =  $3200^\circ$  K.

Using methods for solving the composition of the products of reaction demonstrated in Part II, the composition was found to be

a	3.473
b	0.690
c	0.282
d	0.145
e	0.069
f	0.037
g	0.070
h	3.090

The  $Q_{av}^T$  can now be evaluated for this temperature:

$$Q_{av}^T = \sum Q_f (\text{products}) - \sum Q_f (\text{reactants}) \quad (21)$$

Table III lists values of heats of formation of the chamber and exhaust gases and of the reactants used in evaluating  $Q_{av}^T$ .

With use of Table III,  $Q_{av}^T$  was found to be equal to 218.92 k cal./160.32 gm.

The  $\Delta H_{300}^{3200}$  can now be evaluated.

$$\Delta H_{300}^T = \sum_1 N_1 \Delta H_1 \quad (22)$$

This was computed from Table II and found to be equal to 217.08 k cal./160.32 gm. If the  $Q_{av}^{3200}$  is compared with the  $\Delta H_{300}^{3200}$ , it is found that the temperature of  $3200^\circ$

K chosen for  $T_c$  is too small and a new  $T_c$  must be selected. For the second trial,  $T_c = 3300^\circ \text{K}$  is chosen. Similar calculations are made as with  $T_c = 3200^\circ \text{K}$  and the composition of the products of reaction are found to be

a	3.321
b	0.775
c	0.356
d	0.201
e	0.089
f	0.057
g	0.088
h	3.081

$Q_{av}^{3300}$  and  $\Delta H_{300}^{3300}$  are computed at  $3300^\circ \text{K}$  and found to be:

$$Q_{av}^{3300} = 204.90 \text{ k cal./160.32 gms.}$$

$$\Delta H_{300}^{3300} = 226.11 \text{ k cal./160.32 gms.}$$

Comparing these values, it is seen that  $T_c = 3300^\circ \text{K}$  is too high. Therefore,  $T_c$  must be between  $3200^\circ \text{K}$  and  $3300^\circ \text{K}$ . The exact value of  $T_c$  will be that temperature where  $\Delta H_{300}^{T_c} = Q_{av}^{T_c}$ . With the assumption that  $\Delta H_{300}^{T_c}$  and  $Q_{av}^{T_c}$  versus  $T(^{\circ}\text{K})$  are linear over a  $100^\circ$  temperature range, the  $\Delta T$  (temperature change between the lower and upper temperatures  $T_c$ ) is computed by the following relation:

$$T = 3200^\circ + \Delta T$$

$$\frac{\Delta T}{100}(Q_{av}^{3300} - Q_{av}^{3200}) + Q_{av}^{3200} =$$

$$\frac{\Delta T}{100}(\Delta H_{300}^{3300} - \Delta H_{300}^{3200}) + \Delta H_{300}^{3200} \quad (23)$$

$$\Delta T = 8^\circ \text{ K}$$

$$T_c = 3200 + 8 = 3208^\circ \text{ K}$$

Step B. Calculation of Ratio of Isobaric to Isochoric Heat Capacity ( $\gamma_c$ )

The isobaric and isochoric heat capacities ( $C_{pc}$  and  $C_{vc}$ ) must be calculated in order to obtain  $\gamma_c$ .

$$C_{pc} = \frac{\int_{3200}^{3300} H}{\bar{n}_p(\Delta T)} \quad (24)$$

where  $\int_{3200}^{3300} H = (\Delta H_{300}^{3300} - \Delta H_{300}^{3200}) + (q_{av}^{3200} - q_{av}^{3300}) \quad (25)$

$$\begin{aligned} C_{pc} &= \frac{9.03 - 14.02}{\bar{n}_p(100)} \times 10^3 \text{ cal } ^\circ\text{K}^{-1} \text{ mol}^{-1} \\ &= \frac{23.05 \times 10}{7.912} = 29.133 \text{ cal } ^\circ\text{K}^{-1} \text{ mol}^{-1} \end{aligned}$$

$$C_{vc} = 29.130 - 1.986 = 27.144$$

$$\gamma_c = \frac{C_{pc}}{C_{vc}} = 1.076 \quad (26)$$

Step C. Calculation of Average Molecular Weight ( $\bar{M}_c$ )

$\bar{M}_c$  is the average molecular weight of the products of reaction.

$$\bar{M}_c = \frac{m}{n^{T_c}} \quad (27)$$

where  $m$  = mass of reactants

$n^{T_c}$  = number of moles at temp.  $T_c$  produced by " $m$ " mass of reactants.

$$\bar{M}_c = \frac{160.32}{7.865} = 20.384 \text{ gms. mol}^{-1}$$

Step D. Calculation of Characteristic Velocity (c\*)

Using only the adiabatic flame temperature in the chamber and  $\gamma_c$  and  $\bar{M}_c$  calculated, the parameter, characteristic of the propellant (c\*) can be computed. This is very valuable since the propellant can be immediately judged as to its practicability and may save many useless calculations of propellant systems which would be of no interest.

c\* is defined either of two ways:

$$c^* = \frac{P_c f_t}{\dot{m}} \quad (28)$$

where  $P_c$  = chamber pressure psia

$f_t$  = area of throat

$\dot{m}$  = mass rate of flow through nozzle

or

$$c^* = \frac{a_c}{\Gamma'(\gamma_c)} = \sqrt{\frac{R_u T_c}{\bar{M}_c \gamma_c}} \left[ \frac{1}{\left(\frac{2}{\gamma_c+1}\right)^{\frac{\gamma_c+1}{2(\gamma_c-1)}}} \right] \quad (29)$$

where  $a_c$  = velocity of sound corresponding to chamber conditions

$\Gamma'(\gamma_c)$  = function of  $\gamma$  evaluated at  $\gamma = \gamma_c$

$R_u$  = universal gas constant

$\bar{M}_c$  = average molecular weight of chamber gas

$T_c$  = adiabatic flame temperature in chamber

$\gamma_c$  = ratio of isobaric heat capacity to isochoric heat capacity



The  $\Gamma'(\gamma_c)$  can be found from its relation to  $\gamma_c$  in the equation:

$$\Gamma'(\gamma_c) = \gamma_c \left[ \frac{2}{\gamma_c + 1} \right]^{\frac{\gamma_c + 1}{2(\gamma_c - 1)}} \quad (30)$$

or the linear relation:

$$\Gamma'(\gamma_c) = .1047 + .5048 \gamma_c \quad (31)$$

can be used.

This linear approximation (Cf. Ref. 5) was checked over the range of  $\gamma$  encountered in these calculations and found to be equal to the value calculated by the exact equation within one half per cent.

Using the linear approximation for  $\Gamma'(\gamma_c)$ ,  $c^*$  was calculated to be equal to 6014 ft sec<sup>-1</sup>.

#### Step E. Calculation of Exhaust Temperature ( $T_e$ )

At this point it is important to illustrate two separate methods of calculation: One set of calculations for equilibrium flow (assuming that the composition is a function of the temperature and is changing through the nozzle) and a second set of calculations for constant composition flow (assuming that the composition is independent of temperature and pressure through the nozzle). Calculations for equilibrium flow will be carried out first and then the modifications necessary to calculate constant composition flow are listed.

The exhaust temperature ( $T_e$ ) will be calculated from the relation:

$$T_e = T_c \left( \frac{P_e}{P_c} \right)^{\frac{\bar{\gamma} - 1}{\bar{\gamma}}} = T_c \left( \frac{P_e}{P_c} \right)^{\frac{R_u}{C_p}} \quad (32)$$

### 1. Equilibrium flow.

The composition of the products of reaction is a function of temperature and is continuously changing as the gas flows through the nozzle.

First, estimate  $T_e$  ( $^{\circ}\text{K}$ ) to the nearest 100  $^{\circ}\text{K}$ . Assuming that  $T_e$  is 2200  $^{\circ}\text{K}$ , the composition of the reaction products is calculated by means of the method illustrated in determining the composition in Part II.

a	( $\text{H}_2\text{O}$ )	=	3.983
b	( $\text{H}_2$ )	=	0.380
c	( $\text{OH}$ )	=	0.014
d	( $\text{H}$ )	=	0.009
e	( $\text{O}_2$ )	=	0.001
f	( $\text{O}$ )	=	-
g	( $\text{NO}$ )	=	0.001
h	( $\text{N}_2$ )	=	3.124
n	$T_e$	=	7.512

From this composition at 2200  $^{\circ}\text{K}$ ,  $\Delta H_{300}^{2200}$  was determined to be 129.48 k cal/160.32 gms. and  $\Delta H_{300}^{T_c}$  was previously calculated to be 217.80 k cal/160.32 gms.

The change in the enthalpy of the products of reaction in going from  $T_c$  to  $T_e$  with the components in equilibrium is now calculated:

$$\begin{aligned} \int_{T_c}^{T_e} \Delta H_{300}^{2200} &= (\Delta H_{300}^{T_c} - \Delta H_{300}^{2200}) - (Q_{av}^{2200} - Q_{av}^{T_c}) \\ (Q_{av}^{2200} - Q_{av}^{T_c}) &= 44.04 \text{ k cal/160.32 gms.} \\ \Delta H_{2200}^{T_c} &= 129.48 \text{ k cal/160.32 gms.} \end{aligned}$$

Now  $\bar{C}_p$  can be found for use in determining exhaust temperature ( $T_e$ ). This is the average isobaric heat capacity between the chamber and exit.

$$\bar{C}_p = \frac{\int_{T_e}^{T_c} H_{T_e}^{T_c}}{\bar{n}_p (T_c - T_e)}$$

and since

$$\bar{n}_p = 7.689 \text{ moles}$$

$$\text{and } \int_{T_e}^{T_c} H_{T_e}^{T_c} = 129.48 \text{ k cal/160.32 gms.}$$

$$\text{Then, } \bar{C}_p = 16.690$$

$$\text{and } \frac{R}{\bar{C}_p} = .119$$

Therefore,

$$T_e = T_c (P_e/P_c)^{\frac{R}{\bar{C}_p}} = 2239 \text{ } ^\circ\text{K}$$

It is now necessary to estimate a new  $T_e$  since the  $T_e$  calculated is more than  $\pm 10^\circ$  of the  $T_e$  estimated. Therefore,  $T_e = 2300 \text{ } ^\circ\text{K}$  is now taken and the composition of the products of reaction calculated as before.

$$a \text{ (H}_2\text{O)} = 3.960$$

$$b \text{ (H}_2\text{)} = 0.392$$

$$c \text{ (OH)} = 0.027$$

$$d \text{ (H)} = 0.017$$

$$e \text{ (O}_2\text{)} = 0.003$$

$$f \text{ (O)} = 0.001$$

$$g \text{ (NO)} = 0.006$$

$$h \text{ (N}_2\text{)} = 3.127$$

$$n^{T_e} = 7.528$$

Using method illustrated for computing  $T_e$  from first trial,  $T_e = 2200^\circ\text{K}$ ,

$$\int_{2300}^{T_c} H_{2300} = 119.25 \text{ k cal/160.32 gms.}$$

Now instead of computing  $T_e$  for an assumed  $T_e = 2300^\circ\text{K}$ , it is better to take a new  $T_e$  (assumed) equal to the computed  $T_e$  of first trial (plus or minus a small correction depending on whether or not the first estimate of  $T_e$  was high or low compared to the first calculated value of  $T_e$ ).

For the assumed  $T_e$  so corrected

$$T_e = 2239^\circ\text{K}$$

and  $\int_{2239}^{T_c} H_{2239} = 125.51 \text{ k cal/160.32 gms.}$

from which

$$\bar{C}_p = 16.838$$

and  $\frac{R_u}{\bar{C}_p} = .118$

Hence,  $T_e = T_c \left(\frac{P_e}{P_c}\right)^{\frac{R_u}{\bar{C}_p}} = 2246^\circ\text{K}$

The  $T_e$  calculated is only 7 degrees different from  $T_e$  estimated and can be taken as the correct  $T_e$ . Repetition of the calculation would not change  $T_e$ .

It is noted, however, that the value of  $\int_{T_e}^{T_c} H_{T_e}$  to be used in finding the effective exhaust velocity (c) must be for the correct  $T_e = 2246^\circ\text{K}$  instead of for  $T_e = 2239^\circ\text{K}$ .

$$\int_{2246}^{T_c} H_{2246} = 124.80 \text{ k cal/160.32 gms.}$$

$$\int_{2239}^{T_c} H_{2239} = 125.51 \text{ k cal/160.32 gms.}$$

## 2. Modification for Constant Composition Flow

To modify the calculation of  $T_e$  (equilibrium flow) to apply to a calculation of  $T_e$  (constant composition flow), the following variations must be used.

The composition is not a function of temperature and remains fixed during the flow through the nozzle.

The  $T_e$  estimated must be smaller than  $T_e$  estimated for equilibrium flow.

$$\sum_{T_e}^{T_c} (\Delta H_{300}^{T_c} - \Delta H_{300}^{T_e(\text{est.})}) - 0 \quad (\text{change in enthalpy due to composition changes})$$

Therefore,

$$\sum_{T_e}^{T_c} \Delta H_{T_e}^{T_c}$$

With these modifications the procedure is the same as used for equilibrium flow as illustrated.

## Step F. Calculation of Effective Exhaust Velocity (c) and Specific Impulse (Isp)

The value of effective exhaust velocity (c) is determined from

$$c = \left[ \frac{2 \sum_{T_e}^{T_c} \Delta H_{T_e}^{T_c} J}{M} \right]^{\frac{1}{2}} \quad (33)$$

where  $J$  = mechanical equivalent of heat

The actual formula used was

$$c = 9493.2 \left[ \frac{\sum_{T_e}^{T_c} \Delta H_{T_e}^{T_c}}{M} \right]^{\frac{1}{2}} \text{ ft sec}^{-1}$$

$$c = 8375 \text{ ft sec}^{-1} \text{ for equilibrium flow}$$

$c = 8039 \text{ ft sec}^{-1}$  for constant composition flow

$$I_{sp} = c/g \text{ sec} \quad (34)$$

$$I_{sp} = \frac{8375}{32.2} = 260.1 \text{ sec for equilibrium flow}$$

$$I_{sp} = \frac{8039 \text{ ft sec}^{-1}}{32.2 \text{ ft sec}^{-2}} = 249.6 \text{ sec (constant composition flow)}$$

This value of  $I_{sp}$  represents the theoretical maximum since  $I_{sp}$  is defined by

$$I_{sp} = \frac{F}{\dot{m} g} = \frac{\dot{m} c}{\dot{m} g} = \frac{c}{g}$$

$F = \dot{m} c$  implies that the effective exhaust velocity is equal to the jet velocity which is only true for a perfectly expanded, frictionless nozzle, with true axial flow from nozzle throat.

#### Step G. Calculation of Nozzle Thrust Coefficient ( $C_F$ )

The nozzle thrust coefficient ( $C_F$ ) is a function of  $F$ ,  $P_c$ ,  $f_t$  and is defined as

$$C_F = \frac{F}{P_c f_t} = \frac{c}{c^*} \quad (35)$$

$$C_F = \frac{8375}{6014} = 1.39 \text{ for equilibrium flow}$$

$$C_F = \frac{8034}{6014} = 1.34 \text{ for constant composition flow}$$

#### Step H. Calculation of Altitude Index (h)

The determination of the altitude index is based on values of altitude index and loading factor varying with density and specific impulse.

Arguments of propellant density and specific impulse were used to determine the corresponding altitude index expressed in miles. With this method of determining altitude it was possible to find and plot altitude index as a function of weight percent addition of the third component.

The densities used are those shown in Table IV. It is first necessary to find the average propellant density from the ratio of the molecular weight to the total volume of the reactants.

The propellant mass =  $m = 160.32$  gms.

The total volume equals  $131.72 \text{ cm}^3$ .

$$\bar{\rho} = \frac{m}{\text{Vol}} \quad (36)$$

$$\bar{\rho} = \frac{160.32 \text{ gm}}{131.72 \text{ cm}^3} = 1.22 \text{ gms cm}^{-3}$$

Isp from previous calculation is equal to 249.6 sec (constant composition) and equal to 260.1 sec (equilibrium flow).

With these values of Isp and  $\bar{\rho}$  enter the tables and pick off the corresponding value of altitude index (h) equal 479 miles for constant composition flow and equal to 527 miles for equilibrium flow.



## DISCUSSION OF RESULTS

Considerations have indicated that hydrogen is the best additive to a bipropellant system for reduction of heat transfer because of its high heat capacity per unit weight and its low molecular weight which results in increased performance and reduced combustion temperature providing equilibrium conditions are attained and complete mixing is assumed. In a practical system it is proposed that the addition of hydrogen be accomplished by the use of liquid hydrogen ( $H_2(l)$ ) or by the use of a molecule whose dissociation products are predominantly low molecular weight, i.e., liquid ammonia ( $NH_3(l)$ ). The effect on the performance of the propellant systems,  $N_2O_4 - N_2H_4$ , RFNA -  $N_2H_4$ , and  $H_2O_2 - N_2H_4$ , by addition of liquid hydrogen and liquid ammonia has been calculated for various percentages of additive. These results are tabulated in Tables V to XVI and demonstrated in Figures 1 to 16.

For each tripropellant system a table of all parameters computed assuming equilibrium flow conditions, a table of all parameters computed assuming constant composition flow conditions, curves of chamber temperature, exhaust temperature, specific impulse, and altitude index against weight per cent addition of third component for both equilibrium and constant composition flow, and a curve of percentage variations for these same parameters are presented.

The percentage variation better illustrates the relative effect of the addition of the third component on



the performance parameters. The percentage variations are based on the ratio of the parameter to the stoichiometric value of the system being considered. The change in value of a parameter from the value at stoichiometric can readily be determined from the curve showing this variation as a function of weight per cent addition of the third component. This information is valuable in selecting a propellant system for a given specification.

It is well to note that the constant composition values of the variation of the parameters appear larger than the values of the variation of the parameters for equilibrium flow. It must be remembered that the absolute value of the parameter for equilibrium flow considerations is always greater than or equal to, but never less than the value of the parameter for constant composition considerations.

#### A. ADDITION OF LIQUID HYDROGEN TO A STOICHIOMETRIC MIXTURE OF NITROGEN TETROXIDE AND HYDRAZINE

The addition of hydrogen to the combustion chamber will alter the average molecular weight, the specific heat, and influence the component equilibria. The first effect is sufficient to cause an increase in performance (because of decrease in  $M$ ) at the same time lowering the chamber temperature because of the reduction in available energy and the high heat capacity of hydrogen.

The nitrogen tetroxide-hydrazine system at stoichiometric for equilibrium flow has a high chamber temperature ( $T_c = 3253^\circ \text{K}$ ), a high specific impulse ( $I_{sp} = 259.2 \text{ sec}$ ), a high altitude index ( $h = 525 \text{ mi.}$ ), and a characteristic velocity ( $c^* = 5965 \text{ ft sec}^{-1}$ ). (Cf. Table V.) These results make this a desirable system. However, it is immediately apparent that there are severe temperature problems involved in using this propellant system for long term operation. Therefore, the effect of the addition of hydrogen on this propellant system was evaluated.

The parameters for this system are shown in Figures 1 and 2 and their values are shown in Table V and VI.

Chamber temperature and exhaust temperature both decrease almost linearly with the increase of hydrogen showing approximately 48 per cent drop in chamber temperature with addition of 16.23 per cent by weight hydrogen and approximately 56 per cent decrease in exhaust temperature (constant composition flow) and 65 per cent decrease in exhaust temperature (equilibrium flow) for the same addition by weight hydrogen (16.23 per cent). Thus, it is seen that the effect of the third component on the temperature is desirable.

An increase in specific impulse is observed by the addition of hydrogen reaching a maximum between 8-10 per cent by weight addition of hydrogen. The maximum increase is approximately 11 per cent for constant composition flow consideration and 6.3 per cent for equilibrium flow consideration.

Altitude index shows a 5 per cent increase at approximately 2.5 per cent addition by weight of hydrogen for the assumed constant composition flow process and a 2 per cent increase at 0.5 per cent addition by weight hydrogen for the assumed equilibrium flow condition.

It is well to note that the percentage decrease in altitude index is less than the percentage decrease in chamber temperature, so the overall effect is still favorable. In practice the two factors would have to be carefully weighted depending on the use to which the missile is to be put. For hydrogen addition greater than 5 per cent by weight the percentage decrease in altitude index lags the percentage decrease in chamber temperature by three to ten per cent for equilibrium flow, and for constant composition flow by nine to seventeen per cent.

The effective exhaust velocity ( $c$ ) increases to a maximum of  $8867 \text{ ft sec}^{-1}$  at approximately 9.4 per cent by weight of hydrogen for constant composition flow, and reaches a maximum of  $8868 \text{ ft sec}^{-1}$  for equilibrium flow at approximately the same weight per cent addition of hydrogen as for constant composition flow.

The characteristic velocity follows the effective exhaust velocity reaching a maximum of  $6413 \text{ ft sec}^{-1}$  for the same weight per cent addition of hydrogen.

The thrust coefficient ( $C_F$ ) decreases from 1.48 to 1.38 for constant composition flow and increases from 1.34 to 1.38 for equilibrium flow. The thrust coefficient is

the same for both flow assumptions after the chamber temperature is suppressed to the point where there is no re-association energy appearing in the nozzle expansion.

#### B. ADDITION OF LIQUID AMMONIA TO A STOICHIOMETRIC MIXTURE OF NITROGEN TETROXIDE AND HYDRAZINE

The introduction of low molecular weight constituents into the combustion chamber by the use of liquid ammonia produces results similar to those obtained by adding hydrogen and for missile use the handling problem is greatly simplified. The change in performance is smaller, however.

For this system the results are presented in Tables VII and VIII and Figures 3 and 4.

The exhaust temperature decreases almost linearly with the addition of ammonia showing very little difference for either equilibrium or constant composition flow. For an addition of 17.91 per cent by weight of ammonia a reduction in exhaust temperature of approximately 38 per cent is obtained for equilibrium flow and 21 per cent for constant composition flow.

As can be seen in Figure 3 the change in specific impulse (Isp) reaches a maximum of 251 sec and 260 sec at approximately 5 per cent addition by weight of ammonia for constant composition flow and equilibrium flow respectively.

The chamber temperature decreases steadily with the addition of ammonia, but it is to be noted that for

approximately the same weight per cent addition of ammonia and hydrogen a reduction in chamber temperature of 19 per cent is obtained with liquid ammonia while a reduction of chamber temperature of 48 per cent is obtained by the addition of liquid hydrogen.

Altitude index increases with the addition of ammonia to a maximum ( $h = 527$  miles) at approximately 3 per cent addition by weight ammonia for equilibrium flow. For equilibrium flow the altitude index reaches a maximum ( $h = 483$  miles) at approximately 5 per cent addition by weight of ammonia.

The effective exhaust velocity increases to a maximum of  $8375 \text{ ft sec}^{-1}$  at approximately 2.7 per cent addition by weight of ammonia for equilibrium flow. An increase to a maximum of  $8076 \text{ ft sec}^{-1}$  at 5 per cent addition by weight of ammonia is obtained for constant composition flow.

The characteristic velocity ( $c^*$ ) follows the same trend as the effective exhaust velocity reaching a maximum value of  $6017 \text{ ft sec}^{-1}$  at five per cent ammonia.

The thrust coefficient ( $C_F$ ) changes from 1.40 to 1.38 for equilibrium flow and increases from 1.34 to 1.37 for constant composition flow indicating that the characteristic velocity and specific impulse vary in a similar manner with various percentages of third component.



### C. GENERAL RESULTS APPLICABLE TO ALL SYSTEMS INVESTIGATED

The effect of the addition of hydrogen and ammonia to the other propellant systems is very similar to the effect on the performance and temperature changes for the addition of the third component to the nitrogen-tetroxide systems. Therefore, little would be gained in a detailed discussion of the remaining systems. The results of all the systems are presented in Tables V-XXIV and Figures 1-17.

The calculations for the assumption of constant composition flow in all three systems reveal that the absolute changes are of a smaller order of magnitude on the addition of a third component than are the equilibrium flow results. Actually the flow condition may fall somewhere between the equilibrium flow and constant composition flow assumptions, however, it is well to demonstrate both types of flow as limiting conditions.

A study of the results reveals that:

1. The exhaust temperature for equilibrium flow is affected the most of all,
2. With the exception of the RFNA-NH<sub>3</sub>(l) -N<sub>2</sub>H<sub>4</sub> system the exhaust temperature for constant composition flow is affected to the next greatest extent.
3. The chamber temperature is affected the next greatest extent with the same exception as stated in (2). For weight per cent additions

greater than 6 per cent, (2) and (3) are correct as stated with no exception.

4. Altitude index for equilibrium flow is the parameter affected the next greatest amount.
5. The specific impulse maintains the highest percentage of its value at stoichiometric with the value for variation in specific impulse for constant composition flow being the greater.

If  $E(I_{sp})$  is defined by  $(I_{sp}/I_{sp}^0 - T_c/T_c^0)$  and if  $E(h)$  is defined by  $(h/h^0 - T_c/T_c^0)$ , wherein the superscript term is the value at stoichiometric, it is found that the value of each of these parameters was practically constant for equal percentages of hydrogen for the three systems. The same is true for equal percentages of ammonia added to the three systems.

These values for the hydrogen systems and the ammonia systems were averaged and the average error in the parameter for any system when compared with this mean value for the three systems was small. This is illustrated in the following results for the nitrogen tetroxide-liquid hydrogen-hydrazine system:

<u>Flow</u>	<u>Parameter</u>	<u>Av. Error</u>	<u>Max. Error</u>
Equilibrium	$E_{I_{sp}}$	0.004	0.008
Constant Composition	$E_{I_{sp}}$	0.015	0.021
Equilibrium	$E_h$	0.006	0.007
Constant Composition	$E_h$	0.027	0.030



Similar variations were found for the other systems. The values of these parameters are listed in Tables XVII-XXIV and Figure 17.

The following general results are observed:

1. The amount of the variation of the chamber temperature exceeds the variation in specific impulse and altitude index by a constant value.
2. Hydrogen is more effective than ammonia based on the effect on the performance parameters of the systems under investigation.

The obvious usefulness of these relatively simple parameters lies of course in their adaptability in predicting performances of tripropellant systems once the chamber temperature curves have been calculated or estimated; and as an indirect means for illustrating the relative merit of a series of third components under consideration as possible coolants.

This parameter was applied to data available from other sources. It is shown in Table XVIII that  $E_{isp}$  calculated from data for constant composition for liquid oxygen-liquid hydrogen-hydrazine system (Cf. Ref. 3) was in good agreement with the results discussed before.

In comparison with data for carbonaceous tripropellant systems (Cf. Ref. 4) it was found that agreement was satisfactory with exception that  $E_{isp}$  for system containing carbon was not in sufficient agreement. It is believed, however, that similar parameters might be useful in analyzing

carbonaceous systems at such time as more tripropellant data is available.

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Table XXX. Equilibrium constants.

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TABLE I

Temp. (°K)	$K_1$	$K_2$	$K_3$	$K_4$	$K_5$	$K_6$	$K_7$	$K_8$	$K_9$	$K_{10}$
296.1	$1.007 \times 10^{-5}$	$7.82 \times 10^{24}$		$7.260 \times 10^2$	$1.56 \times 10^{24}$					
700	0.1110	$3.637 \times 10^3$		$9.150 \times 10^{-3}$	$1.06 \times 10^{13}$					
800	2476	31.25		$2.909 \times 10^{-3}$	$9.64 \times 10^{11}$					
900	4546	0.7513		$1.177 \times 10^{-3}$	$1.46 \times 10^{11}$					
1000	7266	0.3720		$5.636 \times 10^{-4}$	$3.29 \times 10^{10}$					
1100	1.058	$3.147 \times 10^{-3}$		$3.070 \times 10^{-4}$	$9.55 \times 10^9$					
1200	1.435	$3.994 \times 10^{-4}$		$1.647 \times 10^{-4}$	$3.39 \times 10^9$					
1300	1.644	$6.975 \times 10^{-5}$		$1.196 \times 10^{-4}$	$1.40 \times 10^9$					
1400	2.270	$1.553 \times 10^{-5}$		$8.239 \times 10^{-5}$	$6.56 \times 10^8$					
1500	2.704	$4.216 \times 10^{-6}$		$5.946 \times 10^{-5}$	$3.36 \times 10^8$					
1600	3.135	$1.348 \times 10^{-6}$		$4.466 \times 10^{-5}$	$1.89 \times 10^8$					
1700	3.555	$4.925 \times 10^{-7}$		$3.479 \times 10^{-5}$	$1.13 \times 10^8$					
1800	3.975	$2.029 \times 10^{-8}$		$2.783 \times 10^{-5}$	$7.06 \times 10^7$					
1900	4.343	$9.211 \times 10^{-9}$		$2.293 \times 10^{-5}$	$4.66 \times 10^7$					
2000	4.782	$4.545 \times 10^{-9}$	$5.736 \times 10^{-6}$	$1.923 \times 10^{-5}$	$3.19 \times 10^7$	$8.13 \times 10^{-6}$	$2.08 \times 10^{-7}$	$8.650 \times 10^{-7}$	$1.629 \times 10^{-3}$	$1.644 \times 10^{-4}$
2100	5.149	$2.393 \times 10^{-9}$	$1.495 \times 10^{-5}$	$1.641 \times 10^{-5}$	$2.26 \times 10^7$	$3.45 \times 10^{-6}$	$6.85 \times 10^{-7}$	$2.460 \times 10^{-6}$	$3.119 \times 10^{-3}$	$3.698 \times 10^{-4}$
2200	5.420	$1.320 \times 10^{-9}$	$3.69 \times 10^{-5}$	$1.421 \times 10^{-5}$	$1.65 \times 10^7$	$1.308 \times 10^{-6}$	$3.34 \times 10^{-6}$	$6.346 \times 10^{-6}$	$5.610 \times 10^{-3}$	$8.072 \times 10^{-4}$
2300	5.653	$7.902 \times 10^{-10}$	$9.39 \times 10^{-5}$	$1.247 \times 10^{-5}$	$1.24 \times 10^7$	$4.19 \times 10^{-6}$	$1.036 \times 10^{-6}$	$1.560 \times 10^{-5}$	$9.893 \times 10^{-3}$	$1.567 \times 10^{-3}$
2400	6.140	$4.673 \times 10^{-10}$	$1.685 \times 10^{-4}$	$1.107 \times 10^{-5}$	$9.46 \times 10^6$	$1.260 \times 10^{-6}$	$3.305 \times 10^{-6}$	$3.475 \times 10^{-5}$	$1.592 \times 10^{-2}$	$2.951 \times 10^{-3}$
2500	6.440	$3.138 \times 10^{-10}$	$3.512 \times 10^{-4}$	$9.95 \times 10^{-6}$	$7.40 \times 10^6$	$3.452 \times 10^{-6}$	$9.121 \times 10^{-6}$	$7.221 \times 10^{-5}$	$2.514 \times 10^{-2}$	$5.230 \times 10^{-3}$
2600	6.668	$2.089 \times 10^{-10}$	$6.74 \times 10^{-4}$	$9.00 \times 10^{-6}$	$5.88 \times 10^6$	$6.65 \times 10^{-6}$	$2.34 \times 10^{-5}$	$1.426 \times 10^{-4}$	$3.337 \times 10^{-2}$	$8.995 \times 10^{-3}$
2700	6.954	$1.435 \times 10^{-10}$	$1.188 \times 10^{-3}$	$8.21 \times 10^{-6}$	$4.74 \times 10^6$	$2.06 \times 10^{-6}$	$5.85 \times 10^{-5}$	$2.678 \times 10^{-4}$	$5.675 \times 10^{-2}$	$1.462 \times 10^{-2}$
2800	7.185	$1.016 \times 10^{-10}$	$2.05 \times 10^{-3}$	$7.56 \times 10^{-6}$	$3.87 \times 10^6$	$4.64 \times 10^{-6}$	$1.243 \times 10^{-4}$	$4.797 \times 10^{-4}$	$9.165 \times 10^{-2}$	$2.312 \times 10^{-2}$
2900	7.376	$7.360 \times 10^{-11}$	$3.42 \times 10^{-3}$	$6.98 \times 10^{-6}$	$3.21 \times 10^6$	$9.90 \times 10^{-6}$	$2.65 \times 10^{-4}$	$6.260 \times 10^{-4}$	$1.148 \times 10^{-1}$	$3.556 \times 10^{-2}$
3000	7.542	$5.458 \times 10^{-11}$	$5.479 \times 10^{-3}$	$6.49 \times 10^{-6}$	$2.69 \times 10^6$	$1.963 \times 10^{-5}$	$5.335 \times 10^{-4}$	$1.373 \times 10^{-3}$	$0.1579$	$5.290 \times 10^{-2}$
3100	7.749		$8.525 \times 10^{-3}$	$2.27 \times 10^6$	$2.27 \times 10^6$	$3.803 \times 10^{-5}$	$1.027 \times 10^{-3}$	$2.210 \times 10^{-3}$	$2.125$	$7.677 \times 10^{-2}$
3200	7.929		$1.294 \times 10^{-2}$	$1.94 \times 10^6$	$1.94 \times 10^6$	$7.055 \times 10^{-5}$	$1.904 \times 10^{-3}$	$3.452 \times 10^{-3}$	$2.813$	$1.087 \times 10^{-1}$
3300	8.078		$1.659 \times 10^{-2}$	$1.66 \times 10^6$	$1.66 \times 10^6$	$1.246 \times 10^{-4}$	$3.389 \times 10^{-3}$	$5.283 \times 10^{-3}$	$3.654$	$1.513 \times 10^{-1}$
3400	8.192		$2.758 \times 10^{-2}$	$1.44 \times 10^6$	$1.44 \times 10^6$	$2.157 \times 10^{-4}$	$3.357 \times 10^{-3}$	$7.398 \times 10^{-3}$	$4.682$	$2.060 \times 10^{-1}$
3500	8.304	$1.621 \times 10^{-10}$	$3.894 \times 10^{-2}$	$4.86 \times 10^{-6}$	$1.26 \times 10^6$	$3.393 \times 10^{-4}$	$9.778 \times 10^{-3}$	$1.192 \times 10^{-2}$	$5.910$	$2.763 \times 10^{-1}$
3600	8.449		$5.404 \times 10^{-2}$		$1.10 \times 10^6$	$5.821 \times 10^{-4}$	$1.591 \times 10^{-1}$	$1.611 \times 10^{-2}$	$7.367$	$3.964 \times 10^{-1}$
3700	8.535		$7.355 \times 10^{-2}$		$9.69 \times 10^5$	$9.886 \times 10^{-4}$	$2.516 \times 10^{-1}$	$2.248 \times 10^{-2}$	$9.064$	$4.691 \times 10^{-1}$
3800	8.664		$9.621 \times 10^{-2}$		$8.59 \times 10^5$	$1.412 \times 10^{-3}$	$3.876 \times 10^{-1}$	$3.068 \times 10^{-2}$	$1.107$	$5.964 \times 10^{-1}$
3900	8.712		$1.300 \times 10^{-1}$		$7.64 \times 10^5$	$2.134 \times 10^{-3}$	$5.678 \times 10^{-1}$	$4.168 \times 10^{-2}$	$1.356$	$7.589 \times 10^{-1}$
4000	8.752	$6.88 \times 10^{-11}$	$1.693 \times 10^{-1}$	$3.94 \times 10^{-6}$	$6.83 \times 10^5$	$3.157 \times 10^{-3}$	$6.711 \times 10^{-1}$	$5.544 \times 10^{-2}$	$1.597$	$9.495 \times 10^{-1}$
4100	8.819		$2.162 \times 10^{-1}$		$6.12 \times 10^5$	$4.526 \times 10^{-3}$	$1.298$	$7.238 \times 10^{-2}$	$1.893$	$1.164$
4200	8.864		$2.760 \times 10^{-1}$		$5.52 \times 10^5$	$6.519 \times 10^{-3}$	$1.806$	$9.423 \times 10^{-2}$	$2.226$	$1.426$
4300	8.898		$3.463 \times 10^{-1}$		$5.01 \times 10^5$	$9.139 \times 10^{-3}$	$2.537$	$1.206 \times 10^{-1}$	$2.596$	$1.730$
4400	8.929		$4.302 \times 10^{-1}$		$4.51 \times 10^5$	$1.263$	$3.508$	$1.526 \times 10^{-1}$	$3.012$	$2.089$
4500	8.952	$3.38 \times 10^{-11}$	$5.291 \times 10^{-1}$	$3.36 \times 10^{-6}$	$4.10 \times 10^5$	$1.718$	$4.778$	$1.916 \times 10^{-1}$	$3.470$	$2.476$
4600	8.974		$6.451 \times 10^{-1}$		$3.74 \times 10^5$	$2.307$	$6.431$	$2.379 \times 10^{-1}$	$3.969$	$2.923$
4700	8.984		$7.799 \times 10^{-1}$		$3.41 \times 10^5$	$3.066$	$8.545$	$3.927 \times 10^{-1}$	$4.320$	$3.432$
4800	8.994		$9.344 \times 10^{-1}$		$3.12 \times 10^5$	$4.015$	$11.21$	$5.370 \times 10^{-1}$	$5.116$	$3.992$
4900	9.003		$1.115$		$2.86 \times 10^5$	$5.226$	$14.59$	$4.321 \times 10^{-1}$	$5.764$	$4.637$
5000	9.012	$2.02 \times 10^{-11}$	$1.315$	$3.00 \times 10^{-6}$	$2.63 \times 10^5$	$6.693$	$16.77$	$5.193 \times 10^{-1}$	$6.461$	$5.317$

• See next page for definitions of  $K_1, K_2, \dots$

Table XXX. [Concluded.]

Temp. (°K)	K <sub>11</sub>	K <sub>12</sub>	K <sub>13</sub>	K <sub>14</sub>	K <sub>15</sub>	K <sub>16</sub>	K <sub>17</sub>
298.1							
400							3.976 × 10 <sup>-5</sup>
500							1.822 × 10 <sup>-5</sup>
600							1.026 × 10 <sup>-5</sup>
700							6.660 × 10 <sup>-6</sup>
800							4.724 × 10 <sup>-6</sup>
900							3.603 × 10 <sup>-6</sup>
1000	2.11 × 10 <sup>-10</sup>					2.220 × 10 <sup>-15</sup>	2.688 × 10 <sup>-6</sup>
1100							2.416 × 10 <sup>-6</sup>
1200							2.081 × 10 <sup>-6</sup>
1300							1.835 × 10 <sup>-6</sup>
1400							1.653 × 10 <sup>-6</sup>
1500	2.98 × 10 <sup>-11</sup>				2.77 × 10 <sup>-6</sup>	9.078 × 10 <sup>-16</sup>	1.510 × 10 <sup>-6</sup>
2000	1.13 × 10 <sup>-11</sup>				2.37 × 10 <sup>-6</sup>	7.290 × 10 <sup>-16</sup>	1.136 × 10 <sup>-6</sup>
2500	6.62 × 10 <sup>-12</sup>				2.23 × 10 <sup>-6</sup>	7.446 × 10 <sup>-16</sup>	9.87 × 10 <sup>-7</sup>
3000		8.27 × 10 <sup>-9</sup>	3.55 × 10 <sup>-7</sup>	1.30 × 10 <sup>-4</sup>	2.16 × 10 <sup>-6</sup>		9.93 × 10 <sup>-7</sup>
3500		3.80 × 10 <sup>-7</sup>	8.45 × 10 <sup>-7</sup>	7.61 × 10 <sup>-4</sup>	2.16 × 10 <sup>-6</sup>		9.89 × 10 <sup>-7</sup>
4000		1.20 × 10 <sup>-6</sup>	1.65 × 10 <sup>-6</sup>	2.15 × 10 <sup>-3</sup>	2.17 × 10 <sup>-6</sup>		9.88 × 10 <sup>-7</sup>
4500		2.92 × 10 <sup>-6</sup>	2.62 × 10 <sup>-6</sup>	4.80 × 10 <sup>-3</sup>	2.22 × 10 <sup>-6</sup>		9.87 × 10 <sup>-7</sup>
5000		5.96 × 10 <sup>-6</sup>	4.41 × 10 <sup>-6</sup>	2.09 × 10 <sup>-3</sup>	2.28 × 10 <sup>-6</sup>		9.88 × 10 <sup>-7</sup>

$$K_1 = P_{CO}P_{H_2O}/P_{CO_2}P_{H_2}; \quad K_2 = P_{CH_4}P_{H_2O}/P_{H_2}^2P_{CO}; \quad K_3 = P_{NO}P_{H_2}/P_{N_2}^{1/2}P_{H_2O};$$

$$K_4 = P_{NH_3}/P_{N_2}^{1/2}P_{H_2}^{3/2}; \quad K_5 = P_{CO}/P_{CO_2}^{1/2}; \quad K_6 = P_{O_2}P_{H_2}^2/P_{H_2O}^2;$$

$$K_7 = P_{O}P_{H_2}/P_{H_2O}; \quad K_8 = P_N/P_{N_2}^{1/2}; \quad K_9 = P_H/P_{H_2}^{1/2}; \quad K_{10} = P_{OH}P_{H_2}^{1/2}/P_{H_2O};$$

$$K_{11} = P_{C_2H_2}P_{H_2O}^2/P_{CO}^2P_{H_2}^3; \quad K_{12} = P_{CH}P_{H_2O}/P_{CO}P_{H_2}^{3/2};$$

$$K_{13} = P_{CN}P_{CO_2}/P_{CO}^2P_{N_2}^{1/2}; \quad K_{14} = P_{NH}/P_{N_2}^{1/2}P_{H_2}^{1/2};$$

$$K_{15} = P_{HCN}P_{H_2O}/P_{CO}P_{H_2}^{3/2}P_{N_2}^{1/2}; \quad K_{16} = P_{C_2N_2}P_{CO_2}^2/P_{CO}^4P_{N_2};$$

$$K_{17} = P_{H_2CO}/P_{H_2}P_{CO}.$$

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TABLE II

ENTHALPY TABLE  
 $\Delta H_{300}^{\circ K}$  kcal/gram mole

$T^{\circ K}$	$H_2$	$H_2O$	CO	$CO_2$	$O_2$	$N_2$	OH	NO	H,N,O	$\Delta T$
300	0.0	0.0	0.0	0.0	0.0	0.0			0.0	0.0
400	0.695	0.811	0.699	0.942	0.721	0.897			0.497	0.199
500	1.393	1.641	1.404	1.970	1.447	1.399			0.993	0.397
600	2.093	2.496	2.125	3.072	2.203	2.112			1.490	0.596
700	2.796	3.380	2.862	4.232	2.981	2.840			1.987	0.795
800	3.502	4.292	3.615	5.441	3.778	3.582			2.484	0.993
900	4.212	5.234	4.386	6.692	4.594	4.343			2.981	1.192
1000	4.931	6.208	5.171	7.976	5.421	5.118	4.985	5.308	3.477	1.390
1100	5.657	7.211	5.973	9.291	6.278	5.907	5.725	6.133	3.974	1.589
1200	6.393	8.247	6.785	10.629	7.135	6.709	6.465	6.958	4.471	1.788
1300	7.138	9.312	7.606	11.989	7.990	7.520	7.233	7.800	4.967	1.986
1400	7.895	10.399	8.437	13.367	8.847	8.342	8.002	8.643	5.464	2.185
1500	8.664	11.519	9.275	14.760	9.704	9.173	8.783	9.499	5.961	2.384
1600	9.439	12.660	10.120	16.168	10.592	10.009	9.584	10.355	6.457	2.582
1700	10.226	13.821	10.972	17.587	11.481	10.854	10.390	11.221	6.954	2.781
1800	11.023	15.006	11.829	19.017	12.369	11.703	11.197	12.088	7.451	2.980
1900	11.828	16.206	12.689	20.455	13.257	12.558	12.015	12.957	7.947	3.178
2000	12.644	17.424	13.554	21.902	14.146	13.417	12.834	13.827	8.444	3.377
2100	13.466	18.659	14.423	23.358	15.061	14.279	13.643	14.700	8.941	3.576
2200	14.295	19.909	15.294	24.820	15.974	15.143	14.506	15.598	9.438	3.774
2300	15.132	21.171	16.169	26.290	16.889	16.013	15.360	16.480	9.935	3.973
2400	15.975	22.446	17.045	27.760	17.802	16.883	16.213	17.364	10.430	4.171
2500	16.827	23.733	17.923	29.242	18.717	17.758	17.080	18.249	10.928	4.370
2600	17.683	25.031	18.807	30.729	19.659	18.636	17.936	19.143	11.425	4.569
2700	18.542	26.338	19.691	32.218	20.601	19.516	18.807	20.036	11.921	4.767
2800	19.410	27.656	20.576	33.712	21.543	20.399	19.678	20.929	12.418	4.966
2900	20.282	28.980	21.464	35.211	22.486	21.284	20.563	21.823	12.915	5.165
3000	21.160	30.315	22.353	36.712	23.427	22.170	21.447	22.716	13.411	5.363
3100	22.041	31.658	23.242	38.222	24.384	23.058	22.335	23.617	13.908	5.562
3200	22.927	33.006	24.136	39.734	25.344	23.947	23.227	24.519	14.405	5.761
3300	23.818	34.362	25.028	41.244	26.308	24.837	24.121	25.421	14.901	5.959
3400	24.712	35.723	25.923	42.764	27.276	25.729	25.021	26.325	15.398	6.158
3500	25.611	37.092	26.818	44.281	28.247	26.622	25.920	27.229	15.894	6.356
3600	26.512	38.466	27.715	45.808	29.219	27.516	26.822	28.135	16.392	6.555
3700	27.416	39.845	28.613	47.332	30.198	28.412	27.730	29.041	16.889	6.754
3800	28.326	41.231	29.512	48.862	31.178	29.307	28.640	29.948	17.385	6.952
3900	29.236	42.619	30.412	50.394	32.164	30.205	29.552	30.856	17.882	7.151
4000	30.153	44.010	31.313	51.930	33.153	31.104	30.467	31.761	18.379	7.350
4100	31.069	45.413	32.215	53.471	34.139	32.006	31.390	32.682	18.875	7.548

SOURCE OF DATA:

THERMODYNAMIC PROPERTIES OF PROPELLANT GASES, HIRSCHFELDER, CURTIS,  
 MCCLURE, AND OSBORNE O. S. R. D. REPORT # 547

NOTE: FOR USE OF THIS TABLE IN CALCULATING THEORETICAL PROPELLANT PERFORMANCE  
 Cf: PROGRESS REPORT 1.25

TABLE III

## HEATS OF FORMATION USED IN THIS INVESTIGATION

$H_2(1)$ .....	1.848 <sup>a</sup> k cal mol <sup>-1</sup>	
$H_2O_2$ .....	44.516 <sup>b</sup>	"
$N_2O_4(1)$ .....	-12.2 <sup>c</sup>	"
$HNO_3$ .....	+41.66 <sup>c</sup>	"
RFNA(6.8% $N_2O_4$ .....	+41.05	"
$N_2H_4$ .....	-12.05	"
$NH_3(1)$ .....	+16.07 <sup>c</sup>	"
$H_2O(g)$ .....	+57.798	"
OH .....	-10.06	"
O .....	-59.159	"
H .....	-52.089	"
NO .....	-21.6 <sup>c</sup>	"

<sup>a</sup>Calculated by L. G. Cole from data in Chemical Rubber Publishing Company Handbook of Chemistry and Physics, pp. 1745-1747 (1945).

<sup>b</sup>Chemical Rubber Publishing Company Handbook of Chemistry and Physics (1947).

<sup>c</sup>Bichowski, F. R., Rossini, F. D., "The Thermochemistry of Chemical Substances" Reinhold Publishing Corporation (1936).

All other data from "Tables of Selected Values of Chemical Thermodynamic Properties", National Bureau of Standards (U. S. Department of Commerce) with support of Office of Naval Research, USN, March 31, 1947.



TABLE IV

## DENSITIES USED IN THIS INVESTIGATION

Component	$\rho_f$ gm cm <sup>-3</sup>
$N_2H_4$	1.01 at 15° C
$H_2O_2$	1.465 at 0° C
$N_2O_4(l)$	1.491 at 0° C
$H_2(l)$	0.07 at -252.8° C
$NH_3(l)$	0.648 at 20° C (Cf. Ref. 14)
$HNO_3(6.8\% N_2O_4)$	1.545 at 20° C

TABLE V

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID HYDROGEN FOR  $\text{N}_2\text{O}_4\text{-H}_2(1)\text{-N}_2\text{H}_4$  SYSTEM  
ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	$T_c$ $^{\circ}\text{K}$	$T_c/T_c^{\circ}$	$T_e$ $^{\circ}\text{K}$	$T_e/T_e^{\circ}$	$\bar{\rho}$ $\text{gm cm}^{-3}$	$\bar{M}$
0.00	0.00	3233	1.000	2334	1.000	1.25	21.446
0.64	0.50	3234	1.000	2270	0.973	1.13	20.407
1.288	1.00	3208	0.992	2149	0.921	1.03	19.413
1.90	1.50	3158	0.977	2037	0.873	0.94	18.452
2.52	2.00	3099	0.959	1930	0.827	0.88	17.597
4.91	4.00	2809	0.868	1598	0.685	0.68	14.866
9.37	8.00	2283	0.706	1185	0.508	0.48	11.475
16.23	15.00	1692	0.523	809	0.347	0.33	8.468

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	$c^*$	$c$	$I_{sp}$	$I_{sp}/I_{sp}^{\circ}$	$C_F$	$h$	$h/h^{\circ}$
	$\text{ft sec}^{-1}$	$\text{ft sec}^{-1}$	$\text{sec}$			$\text{mi.}$	
0.00	5965	8346	259.2	1.000	1.40	525	1.000
0.64	6105	8497	263.9	1.018	1.39	536	1.021
1.28	6198	8587	266.7	1.029	1.38	527	1.004
1.90	6264	8655	268.6	1.037	1.38	521	0.992
2.52	6303	8713	270.6	1.044	1.38	519	0.989
4.91	6390	8825	274.1	1.057	1.38	492	0.937
9.37	6413	8868	275.4	1.063	1.38	420	0.800
16.23	6337	8737	271.3	1.047	1.38	330	0.629

TABLE VI

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID HYDROGEN FOR  $N_2O_4-H_2(1)-N_2H_4$  SYSTEM  
ASSUMING CONSTANT COMPOSITION, FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	$T_c$ °K	$T_c/T_c^\circ$	$T_e$ °K	$T_e/T_e^\circ$	$\bar{P}$ gm cm <sup>-3</sup>	$\bar{M}$
0.00	0.00	3233	1.000	1823	1.000	1.25	20.900
0.64	0.50	3234	1.000	1821	0.999	1.13	19.948
1.28	1.00	3308	0.992	1801	0.988	1.03	19.117
1.90	1.50	3158	0.977	1768	0.970	0.94	18.203
2.52	2.00	3099	0.959	1727	0.947	0.88	17.410
4.91	4.00	2809	0.869	1535	0.837	0.68	14.811
9.37	8.00	2383	0.706	1175	0.645	0.48	11.470
16.23	15.00	1692	0.523	809	0.444	0.33	8.468

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	$c^*$	$c$	$I_{sp}$	$I_{sp}/I_{sp}^\circ$	$C_F$	$h$	$h/h^\circ$
	ft sec <sup>-1</sup>	ft sec <sup>-1</sup>	sec			mi.	
0.00	5965	7970	247.5	1.000	1.34	472	1.000
0.64	6105	8161	253.4	1.024	1.34	489	1.036
1.28	6198	8334	258.5	1.044	1.34	491	1.040
1.90	6264	8436	262.0	1.059	1.35	496	1.051
2.52	6303	8532	265.0	1.071	1.35	496	1.051
4.91	6390	8762	272.1	1.099	1.37	481	1.019
9.37	6413	8867	275.4	1.113	1.38	420	0.880
16.23	6337	8737	271.3	1.096	1.38	330	0.700

TABLE VII

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID AMMONIA FOR  $\text{N}_2\text{O}_4\text{-NH}_3(1)\text{-N}_2\text{H}_4$  SYSTEM  
ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	$T_c$ °K	$T_c/T_c^0$	$T_e$ °K	$T_e/T_e^0$	$\bar{r}$ gm cm <sup>-3</sup>	$\bar{M}$
0.00	0.00	3233	1.000	2334	1.000	1.25	21.446
2.66	0.25	3208	0.992	2246	0.962	1.22	20.842
5.17	0.50	3161	0.978	2102	0.901	1.19	20.214
9.83	1.00	3017	0.933	1842	0.789	1.14	19.071
14.04	1.50	2830	0.875	1628	0.698	1.10	18.088
17.91	2.00	2628	0.813	1456	0.624	1.07	17.253

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	$c^*$ ft sec <sup>-1</sup>	$c$ ft sec <sup>-1</sup>	$I_{sp}$ sec	$I_{sp}/I_{sp}^0$	$C_F$	$h$ mi.	$h/h^0$
0.00	5965	8546	259.2	1.000	1.40	525	1.000
2.66	6014	8375	260.1	1.003	1.39	527	1.004
5.17	6017	8343	259.1	0.999	1.39	523	0.996
9.83	5976	8229	255.6	0.986	1.38	498	0.949
14.04	5848	8073	250.7	0.967	1.38	472	0.899
17.91	5705	7875	244.6	0.944	1.38	439	0.836

TABLE VIII

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID AMMONIA FOR  $N_2O_4-NH_3(1)-N_2H_4$  SYSTEM  
ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	$T_c$ $^{\circ}K$	$T_c/T_c^{\circ}$	$T_e$ $^{\circ}K$	$T_e/T_e^{\circ}$	$\bar{P}$ $gm\ cm^{-3}$	$\bar{M}$
0.00	0.00	3233	1.000	1823	1.000	1.25	20.900
2.66	0.25	3208	0.992	1809	0.992	1.22	20.384
5.17	0.50	3161	0.978	1780	0.976	1.19	19.886
9.83	1.00	3017	0.933	1687	0.925	1.14	18.911
14.04	1.50	2830	0.875	1556	0.854	1.10	18.018
17.91	2.00	2626	0.813	1434	0.787	1.07	17.223

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	$c^*$ $ft\ sec^{-1}$	$c$ $ft\ sec^{-1}$	$I_{sp}$ $sec$	$I_{sp}/I_{sp}^{\circ}$	$C_F$	$h$ $mi.$	$h/h^{\circ}$
0.00	5965	7970	247.5	1.000	1.34	472	1.000
2.66	6014	8039	249.6	1.008	1.34	479	1.015
5.17	6017	8076	250.8	1.013	1.34	483	1.023
9.83	5976	8065	250.5	1.012	1.35	479	1.015
14.04	5848	7996	248.3	1.003	1.37	460	0.975
17.91	5705	7816	242.7	0.981	1.37	424	0.898

TABLE IX

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID HYDROGEN FOR  $\text{H}_2\text{O}_2\text{-H}_2(1)\text{-N}_2\text{H}_4$  SYSTEM  
ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	$T_c$ $^{\circ}\text{K}$	$T_c/T_c^{\circ}$	$T_e$ $^{\circ}\text{K}$	$T_e/T_e^{\circ}$	$\bar{r}$ $\text{gm cm}^{-3}$	$\bar{M}$
0.00	0.00	2851	1.000	1979	1.000	1.28	19.747
1.00	0.50	2843	0.997	1805	0.912	1.09	18.250
1.97	1.00	2749	0.964	1670	0.844	0.95	16.951
2.93	1.50	2639	0.926	1544	0.780	0.85	15.831
3.87	2.00	2527	0.886	1445	0.730	0.77	14.854
7.46	4.00	2140	0.751	1144	0.578	0.56	12.013
13.88	8.00	1628	0.571	798	0.403	0.38	8.938
23.21	15.00	1143	0.401	528	0.267	0.26	6.515
(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	$c^*$ $\text{ft sec}^{-1}$	$c$ $\text{ft sec}^{-1}$	$I_{sp}$ $\text{sec}$	$I_{sp}/I_{sp}^{\circ}$	$C_F$	$h$ $\text{mi.}$	$h/h^{\circ}$
0.00	5775	8067	250.5	1.000	1.40	491	1.000
1.00	5952	8221	255.3	1.019	1.39	487	0.992
1.97	5976	8290	257.5	1.028	1.39	475	0.967
2.93	6012	8349	259.3	1.035	1.39	462	0.941
3.87	6044	8396	260.7	1.041	1.39	456	0.929
7.46	6095	8461	262.8	1.049	1.39	409	0.833
13.88	6085	8396	260.7	1.041	1.38	326	0.664
23.21	5866	8128	252.4	1.008	1.38	227	0.462

TABLE X

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID HYDROGEN FOR  $\text{H}_2\text{O}_2\text{-H}_2(1)\text{-N}_2\text{H}_4$  SYSTEM  
ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	$T_c$ $^{\circ}\text{K}$	$T_c/T_c^{\circ}$	$T_e$ $^{\circ}\text{K}$	$T_e/T_e^{\circ}$	$\bar{p}$ $\text{gm cm}^{-3}$	$\bar{M}$
0.00	0.00	2851	1.000	1694	1.000	1.28	19.418
1.00	0.50	2843	0.997	1677	0.990	1.09	18.126
1.97	1.00	2749	0.964	1600	0.945	0.95	16.892
2.93	1.50	2659	0.926	1512	0.893	0.85	15.604
3.87	2.00	2527	0.886	1428	0.843	0.77	14.840
7.46	4.00	2140	0.751	1141	0.676	0.56	12.010
13.88	8.00	1628	0.571	798	0.471	0.38	8.938
23.21	15.00	1143	0.401	528	0.312	0.26	6.515

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	$c^*$	$c$	$I_{sp}$	$I_{sp}/I_{sp}^{\circ}$	$C_F$	$h$	$h/h^{\circ}$
	$\text{ft sec}^{-1}$	$\text{ft sec}^{-1}$	$\text{sec}$			$\text{mi.}$	
0.00	5775	7852	243.8	1.000	1.36	458	1.000
1.00	5932	8107	251.8	1.033	1.37	474	1.035
1.97	5976	8234	255.7	1.049	1.38	468	1.022
2.93	6012	8320	258.4	1.060	1.38	458	1.000
3.87	6044	8365	259.8	1.066	1.38	455	0.993
7.46	6095	8459	262.7	1.078	1.39	409	0.893
13.88	6083	8396	260.7	1.069	1.38	326	0.712
23.21	5886	8128	252.4	1.035	1.38	227	0.496

TABLE XI

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID AMMONIA FOR  $\text{H}_2\text{O}_2\text{-NH}_3(1)\text{-N}_2\text{H}_4$  SYSTEM  
ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	$T_c$ $^{\circ}\text{K}$	$T_c/T_c^{\circ}$	$T_e$ $^{\circ}\text{K}$	$T_e/T_e^{\circ}$	$\bar{p}$ $\text{gm cm}^{-3}$	$\bar{M}$
0.00	0.00	2851	1.000	1979	1.000	1.28	19.747
4.08	0.25	2804	0.983	1767	0.893	1.23	18.851
7.84	0.50	2677	0.939	1606	0.812	1.19	18.049
14.54	1.00	2376	0.833	1342	0.678	1.12	16.719
20.32	1.50	2099	0.736	1140	0.576	1.07	15.698
25.38	2.00	1862	0.653	977	0.494	1.03	14.901

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	$c^*$	$c$	$I_{sp}$	$I_{sp}/I_{sp}^{\circ}$	$C_F$	$h$	$h/h^{\circ}$
	$\text{ft sec}^{-1}$	$\text{ft sec}^{-1}$	$\text{sec}$			$\text{mi.}$	
0.00	5773	8067	250.5	1.000	1.40	489	1.000
4.08	5804	8035	249.5	0.996	1.38	479	0.980
7.84	5699	7922	246.0	0.982	1.39	460	0.941
14.54	5487	7648	237.5	0.948	1.39	419	0.857
20.32	5283	7351	228.3	0.911	1.39	371	0.759
25.38	5081	7048	218.9	0.874	1.39	333	0.681



TABLE XII

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID AMMONIA FOR  $\text{H}_2\text{O}_2\text{-NH}_3(1)\text{-N}_2\text{H}_4$  SYSTEM  
ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	$T_c$ $^{\circ}\text{K}$	$T_c/T_c^{\circ}$	$T_e$ $^{\circ}\text{K}$	$T_e/T_e^{\circ}$	$\bar{\rho}$ $\text{gm cm}^{-3}$	$\bar{M}$
0.00	0.00	2851	1.000	1694	1.000	1.28	19.418
4.08	0.25	2804	0.983	1654	0.976	1.23	18.732
7.84	0.50	2677	0.939	1553	0.917	1.19	18.001
14.54	1.00	2376	0.833	1333	0.787	1.12	16.710
20.32	1.50	2099	0.736	1138	0.672	1.07	15.696
25.38	2.00	1862	0.653	977	0.577	1.03	14.901

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	$c^*$	$c$	$I_{sp}$	$I_{sp}/I_{sp}^{\circ}$	$C_F$	$h$	$h/h^{\circ}$
	ft sec $^{-1}$	ft sec $^{-1}$	sec			mi.	
0.00	5773	7852	245.8	1.000	1.36	460	1.000
4.08	5804	7916	245.8	1.008	1.36	462	1.004
7.84	5699	7876	244.6	1.003	1.38	458	0.996
14.54	5487	7637	237.2	0.969	1.39	419	0.911
20.32	5283	7346	228.1	0.936	1.39	371	0.807
25.38	5081	7048	218.9	0.898	1.39	333	0.724

TABLE XIII

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID HYDROGEN FOR RFNA-H<sub>2</sub>(1)-N<sub>2</sub>H<sub>4</sub> SYSTEM  
ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	T <sub>c</sub> °K	T <sub>c</sub> /T <sub>c</sub> <sup>0</sup>	T <sub>e</sub> °K	T <sub>e</sub> /T <sub>e</sub> <sup>0</sup>	$\bar{P}$ gm cm <sup>-3</sup>	$\bar{M}$
0.00	0.00	2957	1.000	2037	1.000	1.28	21.367
0.90	0.50	2949	0.997	1858	0.912	1.11	19.791
1.79	1.00	2856	0.966	1716	0.842	0.98	18.413
2.65	1.50	2746	0.929	1593	0.782	0.88	17.201
3.51	2.00	2632	0.890	1490	0.731	0.79	16.153
6.78	4.00	2229	0.754	1179	0.579	0.59	13.064
13.46	8.00	1680	0.568	816	0.401	0.40	9.693
21.43	15.00	1184	0.400	543	0.276	0.27	7.019

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	c*	c	I <sub>sp</sub>	I <sub>sp</sub> /I <sub>sp</sub> <sup>0</sup>	C <sub>F</sub>	h	h/h <sup>0</sup>
	ft sec <sup>-1</sup>	ft sec <sup>-1</sup>	sec			mi.	
0.00	5660	7870	244.4	1.000	1.39	460	1.000
0.90	5811	8028	249.3	1.020	1.38	468	1.017
1.79	5844	8107	251.8	1.030	1.39	458	0.996
2.65	5898	8160	253.4	1.037	1.38	449	0.976
3.51	5909	8193	254.4	1.041	1.39	436	0.948
6.78	5958	8245	256.1	1.048	1.38	386	0.839
13.46	5927	8179	254.0	1.039	1.38	313	0.680
21.43	5764	7889	245.0	1.002	1.38	212	0.461

TABLE XIV

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID HYDROGEN FOR RFNA-H<sub>2</sub>(1)-N<sub>2</sub>H<sub>4</sub> SYSTEM  
ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	T <sub>c</sub> °K	T <sub>c</sub> /T <sub>c</sub> <sup>0</sup>	T <sub>e</sub> °K	T <sub>e</sub> /T <sub>e</sub> <sup>0</sup>	$\bar{P}$ gm cm <sup>-3</sup>	$\bar{M}$
0.00	0.00	2957	1.000	1703	1.000	1.28	21.006
0.90	0.50	2942	0.997	1696	0.996	1.11	19.614
1.79	1.00	2856	0.966	1619	0.951	0.98	18.320
2.65	1.50	2746	0.929	1540	0.904	0.88	17.149
3.51	2.00	2632	0.890	1455	0.854	0.79	16.126
6.78	4.00	2229	0.754	1173	0.689	0.59	13.063
13.46	8.00	1680	0.568	816	0.479	0.40	9.693
21.43	15.00	1184	0.400	543	0.319	0.27	7.019

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	c*	c	I <sub>sp</sub>	I <sub>sp</sub> /I <sub>sp</sub> <sup>0</sup>	C <sub>F</sub>	h	h/h <sup>0</sup>
	ft sec <sup>-1</sup>	ft sec <sup>-1</sup>	sec			mi.	
0.00	5660	7638	257.2	1.000	1.35	437	1.000
0.90	5811	7882	244.8	1.028	1.36	447	1.023
1.79	5844	8022	249.1	1.046	1.37	447	1.023
2.65	5898	8096	251.4	1.055	1.37	441	1.009
3.51	5909	8155	253.3	1.063	1.38	430	0.984
6.78	5958	8244	256.0	1.075	1.38	386	0.883
13.46	5927	8179	254.0	1.066	1.38	313	0.716
21.43	5764	7889	243.0	1.030	1.38	212	0.465

TABLE XV

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID AMMONIA FOR RFNA-NH<sub>3</sub>(1)-N<sub>2</sub>H<sub>4</sub> SYSTEM  
ASSUMING EQUILIBRIUM FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	T <sub>c</sub> °K	T <sub>c</sub> /T <sub>c</sub> <sup>o</sup>	T <sub>e</sub> °K	T <sub>e</sub> /T <sub>e</sub> <sup>o</sup>	gm cm <sup>-3</sup>	$\bar{M}$
0.00	0.00	2957	1.000	2037	1.000	1.28	21.367
3.70	0.25	2913	0.985	1823	0.895	1.24	20.384
7.13	0.50	2783	0.941	1648	0.809	1.20	19.491
13.31	1.00	2479	0.838	1385	0.680	1.13	17.995
18.72	1.50	2193	0.742	1177	0.578	1.08	16.838
23.49	2.00	1948	0.659	1008	0.495	1.04	15.823

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	c*	c	I <sub>sp</sub>	I <sub>sp</sub> /I <sub>sp</sub> <sup>o</sup>	C <sub>F</sub>	h	h/h <sup>o</sup>
	ft sec <sup>-1</sup>	ft sec <sup>-1</sup>	sec			mi.	
0.00	5660	7870	244.4	1.000	1.39	460	1.000
3.70	5703	7863	244.2	0.999	1.38	460	1.000
7.13	5587	7774	241.4	0.988	1.39	441	0.959
13.31	5418	7508	233.2	0.954	1.39	405	0.880
18.72	5206	7228	224.5	0.919	1.39	358	0.778
23.49	5018	6958	216.1	0.884	1.39	314	0.683

TABLE XVI

VARIATION OF PERFORMANCE PARAMETERS WITH WEIGHT PER CENT  
OF LIQUID AMMONIA FOR RFNA-NH<sub>3</sub>(1)-N<sub>2</sub>H<sub>4</sub> SYSTEM  
ASSUMING CONSTANT COMPOSITION FLOW CONDITIONS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
WT%	MOLES	T <sub>c</sub> °K	T <sub>c</sub> /T <sub>c</sub> <sup>o</sup>	T <sub>e</sub> °K	T <sub>e</sub> /T <sub>e</sub> <sup>o</sup>	$\bar{P}$ gm cm <sup>-3</sup>	$\bar{M}$
0.00	0.00	2957	1.000	1703	1.000	1.28	21.006
3.70	0.25	2913	0.985	1669	0.998	1.24	20.216
7.13	0.50	2783	0.941	1578	0.927	1.20	19.414
13.31	1.00	2479	0.838	1363	0.800	1.13	17.977
18.72	1.50	2193	0.742	1173	0.689	1.08	16.840
23.49	2.00	1948	0.659	1008	0.592	1.04	15.923

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
WT%	c*	c	I <sub>sp</sub>	I <sub>sp</sub> /I <sub>sp</sub> <sup>o</sup>	C <sub>F</sub>	h mi.	h/h <sup>o</sup>
	ft sec <sup>-1</sup>	ft sec <sup>-1</sup>	sec				
0.00	5660	7667	238.1	1.000	1.35	437	1.000
3.70	5703	7731	240.1	1.008	1.36	441	1.009
7.13	5587	7690	238.8	1.003	1.38	432	0.989
13.31	5418	7487	232.5	0.976	1.38	402	0.920
18.72	5206	7209	223.9	0.940	1.38	354	0.810
23.49	5018	6958	216.1	0.908	1.39	314	0.719

TABLE XVII

VARIATION OF  $E(I_{sp})$  WITH WEIGHT PER CENT OF LIQUID HYDROGEN  
FOR EQUILIBRIUM FLOW CONDITIONS

Propellant systems:

A.  $N_2O_4-H_2(1)-N_2H_4$

B.  $H_2O_2-H_2(1)-N_2H_4$

C. RFNA- $H_2(1)-N_2H_4$

Wt.% $H_2(1)$	A	B	C	Average of A,B,C
0.00	0.000	0.000	0.000	0.000
3.00	0.108	0.110	0.124	0.114
6.00	0.236	0.240	0.256	0.244
8.00	0.320	0.314	0.329	0.321
10.00	0.385	0.374	0.388	0.382
12.00	0.440	0.428	0.436	0.435
15.00	0.506	0.496	0.504	0.502
20.00	-	0.580	0.587	0.583
Average Error	0.004	0.006	0.006	
Max. Error	0.008	0.008	0.010	

Errors are with respect to average value obtained  
by averaging  $E(I_{sp})$  of systems A, B, and C.

TABLE XVIII

VARIATION OF  $E(I_{sp})$  WITH WEIGHT PER CENT OF LIQUID HYDROGEN  
FOR CONSTANT COMPOSITION FLOW-CONDITIONS

Propellant Systems:

- A.  $N_2O_4-H_2(1)-N_2H_4$
- B.  $H_2O_2-H_2(1)-N_2H_4$
- C. RFNA- $H_2(1)-N_2H_4$
- D.  $O_2(1)-H_2(1)-N_2H_4^{(a)}$

Wt. % $H_2(1)$	A	B	C	Average of A, B & C	D
0.00	0.000	0.000	0.000	0.000	0.000
3.00	0.114	0.134	0.144	0.131	0.124
6.00	0.280	0.266	0.282	0.276	0.250
8.00	0.368	0.343	0.356	0.356	0.323
10.00	0.436	0.400	0.416	0.417	0.392
12.00	0.490	0.452	0.464	0.469	0.452
15.00	0.556	0.522	0.530	0.536	0.528
20.00	-	0.606	0.614	0.610	0.630
Average Error	0.015	0.011	0.005		0.016
Max. Error	0.021	0.017	0.013		0.026

Errors are with respect to average value obtained  
by averaging  $E(I_{sp})$  of systems A, B and C.

(a) Data was computed from values listed in Ref. 3.



TABLE XIX

VARIATION OF  $E(h)$  WITH WEIGHT PER CENT OF LIQUID HYDROGEN  
FOR EQUILIBRIUM FLOW CONDITIONS

## Propellant Systems:

A.  $N_2O_4-H_2(1)-N_2H_4$ B.  $H_2O_2-H_2(1)-N_2H_4$ C. RFNA- $H_2(1)-N_2H_4$ 

Wt.% $H_2(1)$	A	B	C	Average of A,B&C
0.00	0.000	0.000	0.000	0.000
3.00	0.040	0.032	0.052	0.038
6.00	0.080	0.064	0.074	0.073
8.00	0.094	0.088	0.080	0.087
10.00	0.100	0.094	0.089	0.094
12.00	0.105	0.095	0.096	0.099
15.00	0.108	0.096	0.100	0.101
20.00	-	0.080	0.068	0.073
Average Error	0.006	0.006	0.006	
Max. Error	0.007	0.016	0.014	

Errors are with respect to average value obtained by averaging  $E(h)$  of systems A, B and C.

TABLE XX

VARIATION OF  $E(h)$  WITH WEIGHT PER CENT OF LIQUID HYDROGEN  
FOR CONSTANT COMPOSITION FLOW CONDITIONS

Propellant Systems:

A.  $N_2O_4-H_2(1)-N_2H_4$

B.  $H_2O_2-H_2(1)-N_2H_4$

C. RFNA- $H_2(1)-N_2H_4$

Wt.% $H_2(1)$	A	B	C	Average of A, B & C
0.00	0.000	0.000	0.000	0.000
3.00	0.113	0.080	0.086	0.093
6.00	0.164	0.130	0.116	0.137
8.00	0.184	0.149	0.128	0.154
10.00	0.188	0.152	0.136	0.159
12.00	0.190	0.148	0.143	0.160
15.00	0.180	0.144	0.140	0.155
20.00	-	0.124	0.106	0.115
Average Error	0.027	0.009	0.017	
Max. Error	0.030	0.013	0.026	

Errors are with respect to average value obtained  
by averaging  $E(h)$  for systems A, B and C.

TABLE XXI

VARIATION OF  $E(I_{sp})$  WITH WEIGHT PER CENT OF LIQUID AMMONIA  
FOR EQUILIBRIUM FLOW CONDITIONS

Propellant Systems:

D.  $N_2O_4-NH_3(1)-N_2H_4$

E.  $H_2O_2-NH_3(1)-N_2H_4$

F. RFNA- $NH_3(1)-N_2H_4$

Wt.% $NH_3(1)$	D	E	F	Average of D, E & F
0.00	0.000	0.000	0.000	0.000
3.00	0.012	0.010	0.010	0.011
6.00	0.032	0.028	0.034	0.031
8.00	0.044	0.044	0.056	0.048
10.00	0.060	0.064	0.078	0.067
12.00	0.078	0.088	0.100	0.089
15.00	0.106	0.120	0.136	0.121
20.00	-	0.172	0.190	0.181
Average Error	0.007	0.003	0.008	
Max. Error	0.015	0.009	0.015	

Errors are with respect to average value obtained by  
averaging  $E(I_{sp})$  for systems D, E and F.

TABLE XXII

VARIATION OF  $E(I_{sp})$  WITH WEIGHT PER CENT OF LIQUID AMMONIA  
FOR CONSTANT COMPOSITION FLOW CONDITIONS

## Propellant Systems:

D.  $N_2O_4-NH_3(1)-N_2H_4$ E.  $H_2O_2-NH_3(1)-N_2H_4$ F. RFNA- $NH_3(1)-N_2H_4$ 

Wt.% $NH_3(1)$	D	E	F	Average of D, E, & F
0.00	0.000	0.000	0.000	0.000
3.00	0.020	0.020	0.018	0.019
6.00	0.044	0.044	0.050	0.046
8.00	0.063	0.064	0.076	0.068
10.00	0.084	0.086	0.100	0.090
12.00	0.107	0.110	0.123	0.113
15.00	0.141	0.144	0.156	0.147
20.00	-	0.196	0.210	0.203
Average Error	0.004	0.003	0.007	
Max. Error	0.006	0.007	0.010	

Errors are with respect to average value obtained  
by averaging  $E(I_{sp})$  for systems D, E, and F.

TABLE XXIII

VARIATION OF  $E(h)$  WITH WEIGHT PER CENT OF LIQUID AMMONIA  
FOR EQUILIBRIUM FLOW CONDITIONS

## Propellant Systems:

D.  $N_2O_4-NH_3(1)-N_2H_4$ E.  $H_2O_2-NH_3(1)-N_2H_4$ F. RFNA- $NH_3(1)-N_2H_4$ 

Wt.% $NH_3(1)$	D	E	F	Average of D, E & F
0.00	0.000	0.000	0.000	0.000
3.00	0.012	0.000	0.010	0.007
6.00	0.020	0.000	0.016	0.012
8.00	0.020	0.003	0.023	0.015
10.00	0.021	0.008	0.032	0.020
12.00	0.024	0.016	0.040	0.027
15.00	0.028	0.023	0.042	0.031
20.00	-	0.028	0.032	0.030
Average Error	0.004	0.009	0.007	
Max. Error	0.008	0.012	0.013	

Errors are with respect to average value obtained by averaging  $E(h)$  for systems D, E, and F.

TABLE XXIV

VARIATION OF  $E(h)$  WITH WEIGHT PER CENT OF LIQUID AMMONIA  
FOR CONSTANT COMPOSITION FLOW CONDITIONS.

Propellant Systems:

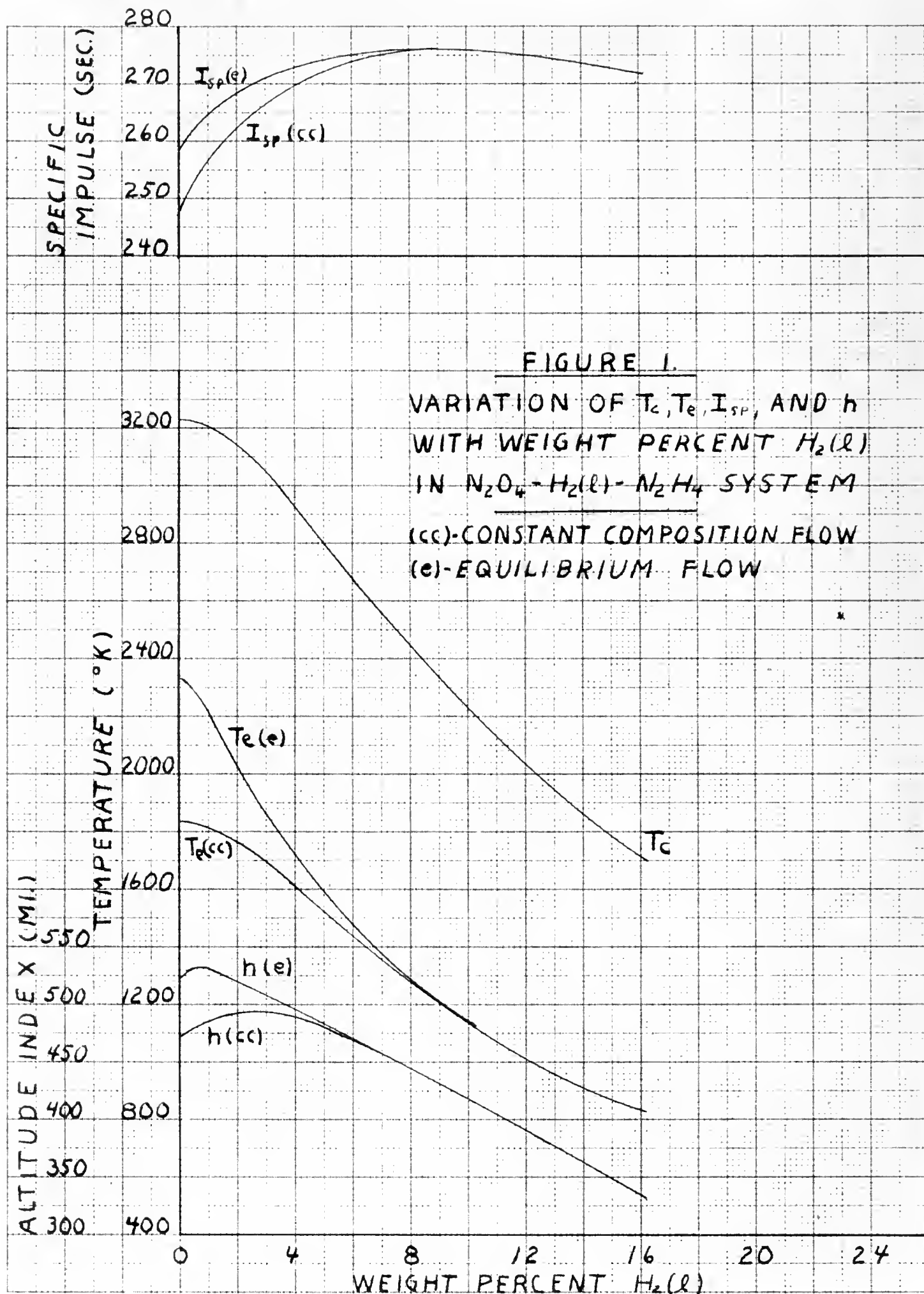
D.  $N_2O_4-NH_3(1)-N_2H_4$

E.  $H_2O_2-NH_3(1)-N_2H_4$

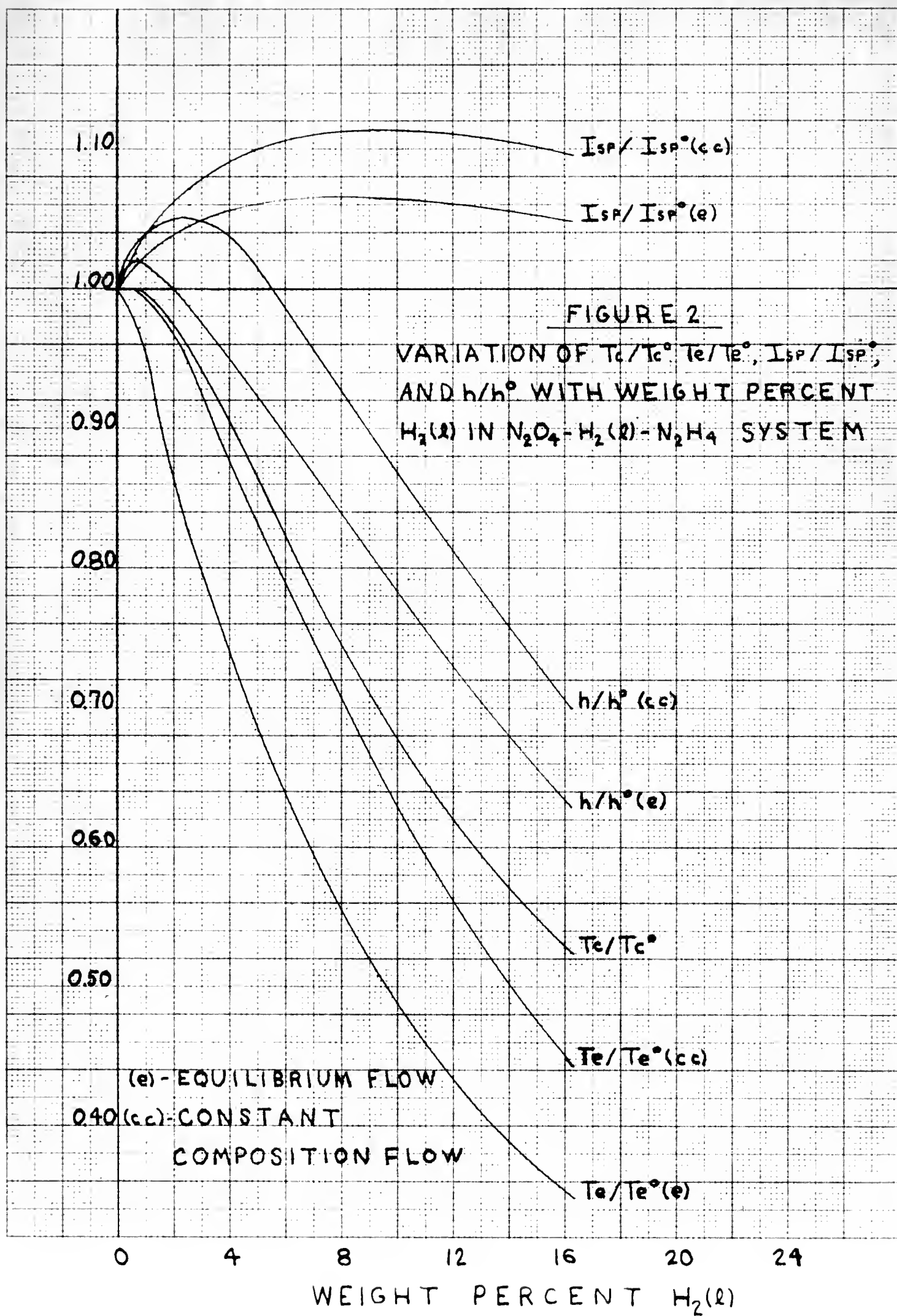
F. RFNA- $NH_3(1)-N_2H_4$

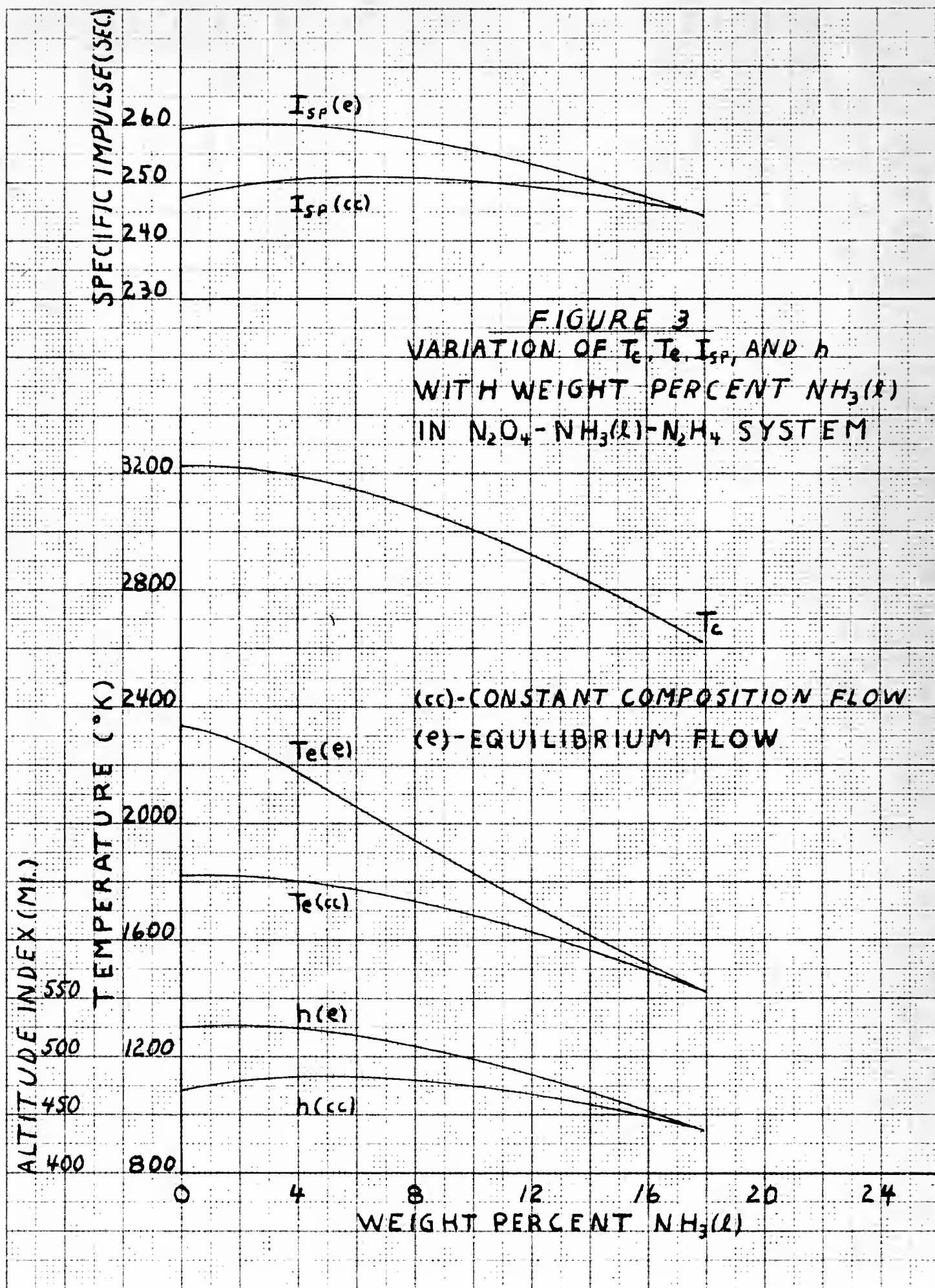
Wt.% $NH_3(1)$	D	E	F	Average of D, E and F
0.00	0.000	0.000	0.000	0.000
3.00	0.028	0.016	0.018	0.021
6.00	0.060	0.042	0.042	0.048
8.00	0.076	0.058	0.060	0.065
10.00	0.088	0.070	0.072	0.077
12.00	0.103	0.080	0.080	0.088
15.00	0.106	0.080	0.084	0.090
20.00	-	0.070	0.064	0.067
Average Error	0.012	0.007	0.005	
Max. Error	0.016	0.010	0.008	

Errors are with respect to average value obtained by averaging  $E(h)$  for systems D, E and F.

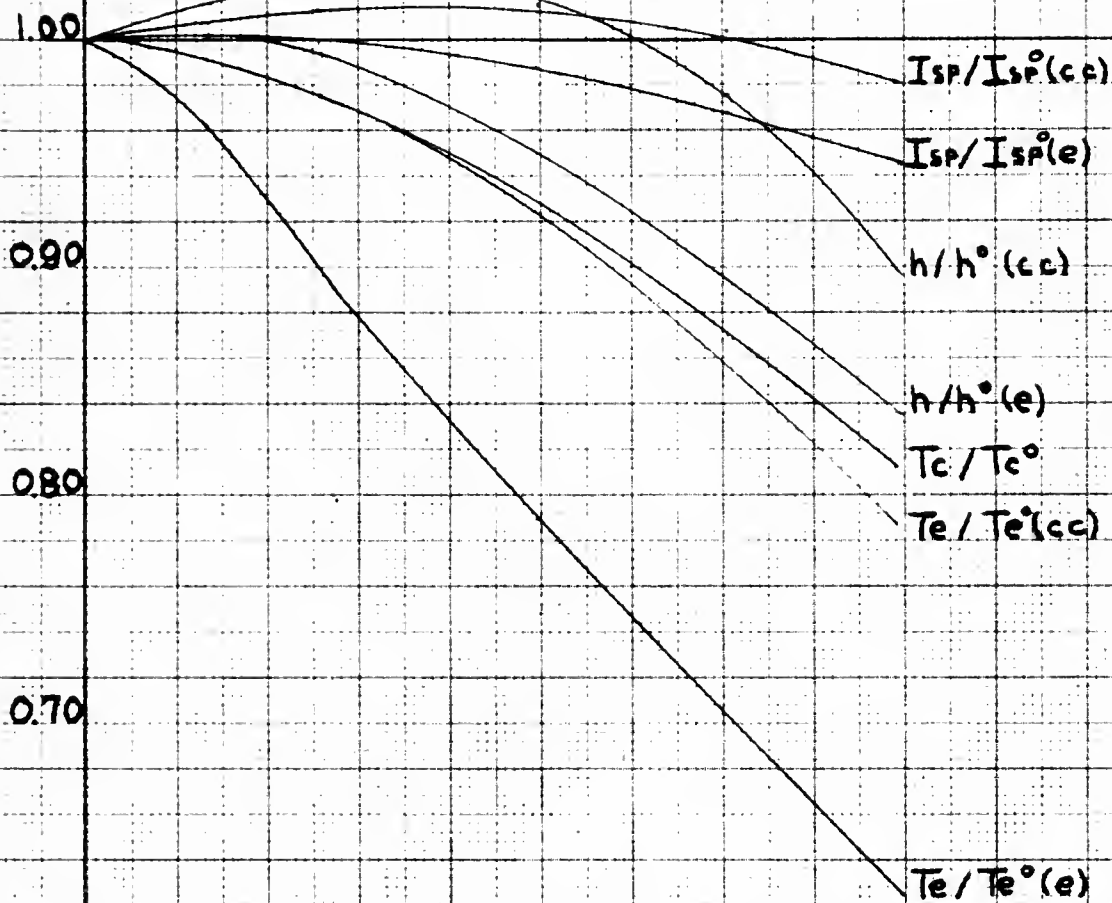








**FIGURE 4**  
**VARIATION OF  $T_c/T_c^\circ$ ,  $T_e/T_e^\circ$ ,  $I_{sp}/I_{sp}^\circ$ , AND  $h/h^\circ$  WITH WEIGHT PERCENT  $\text{NH}_3(\ell)$  IN  $\text{N}_2\text{O}_4$ - $\text{NH}_3(\ell)$ - $\text{N}_2\text{H}_4$  SYSTEM**

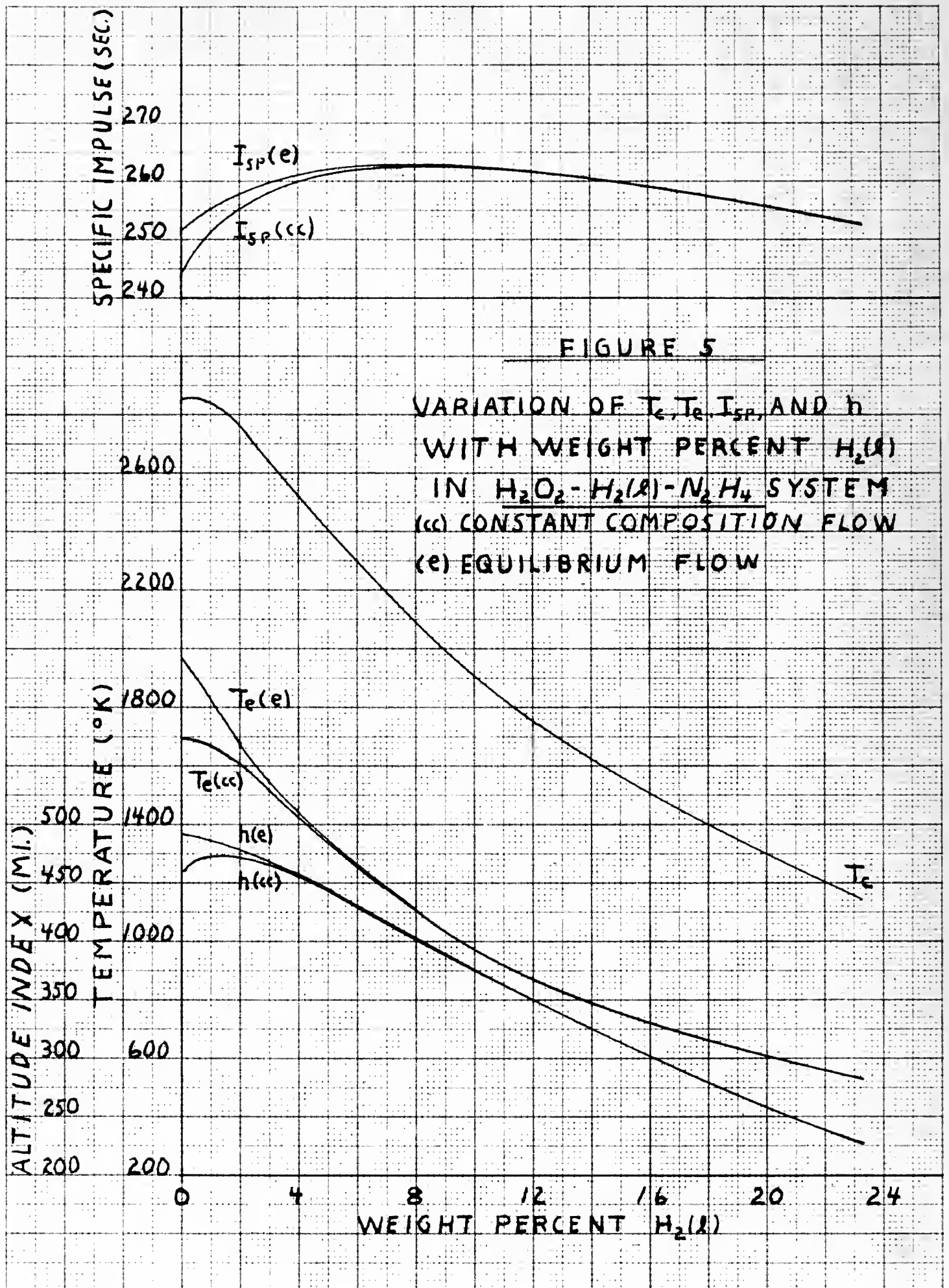


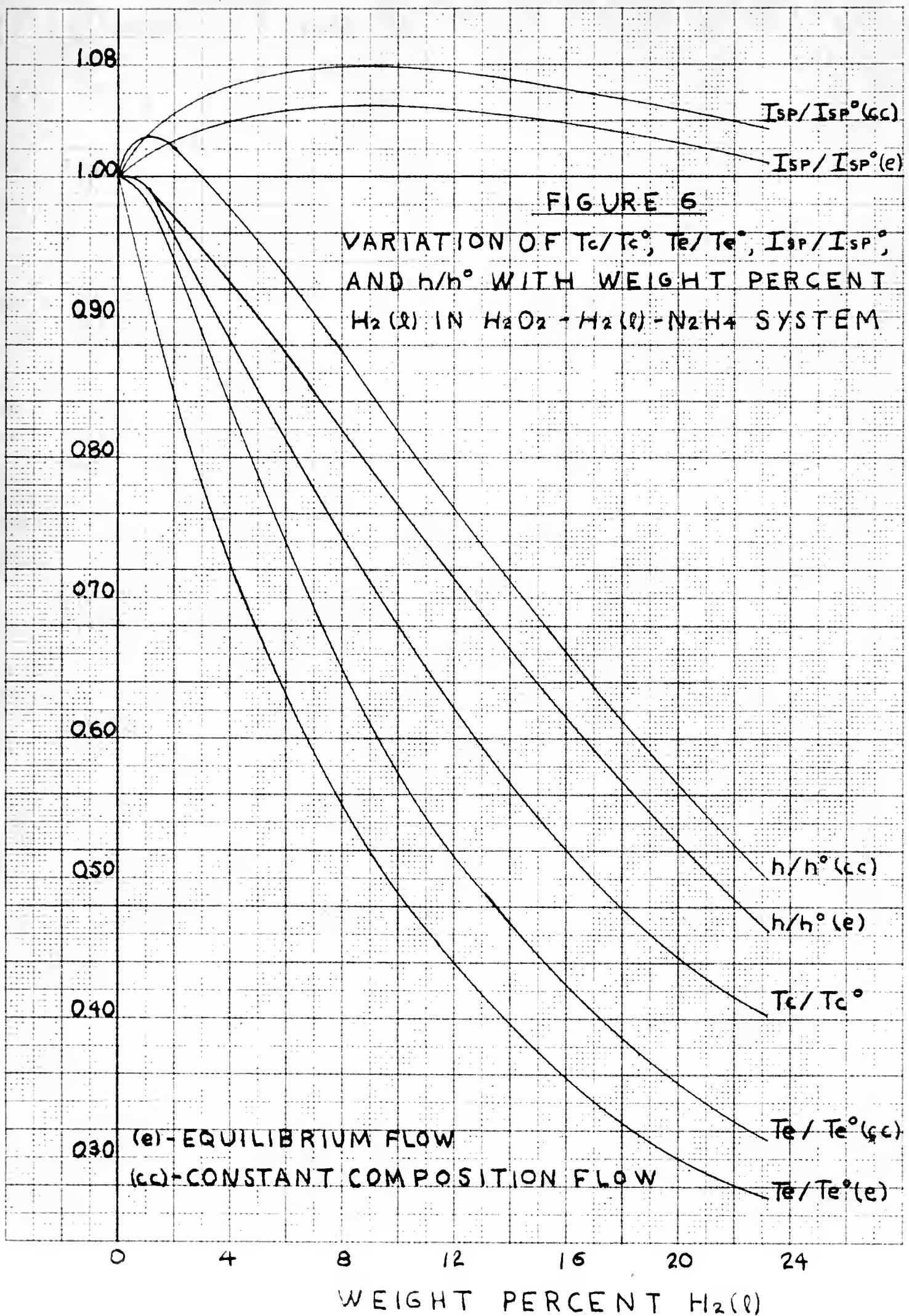
(e)-EQUILIBRIUM FLOW

(cc)-CONSTANT COMPOSITION FLOW

0 4 8 12 16 20 24

WEIGHT PERCENT  $\text{NH}_3(\ell)$







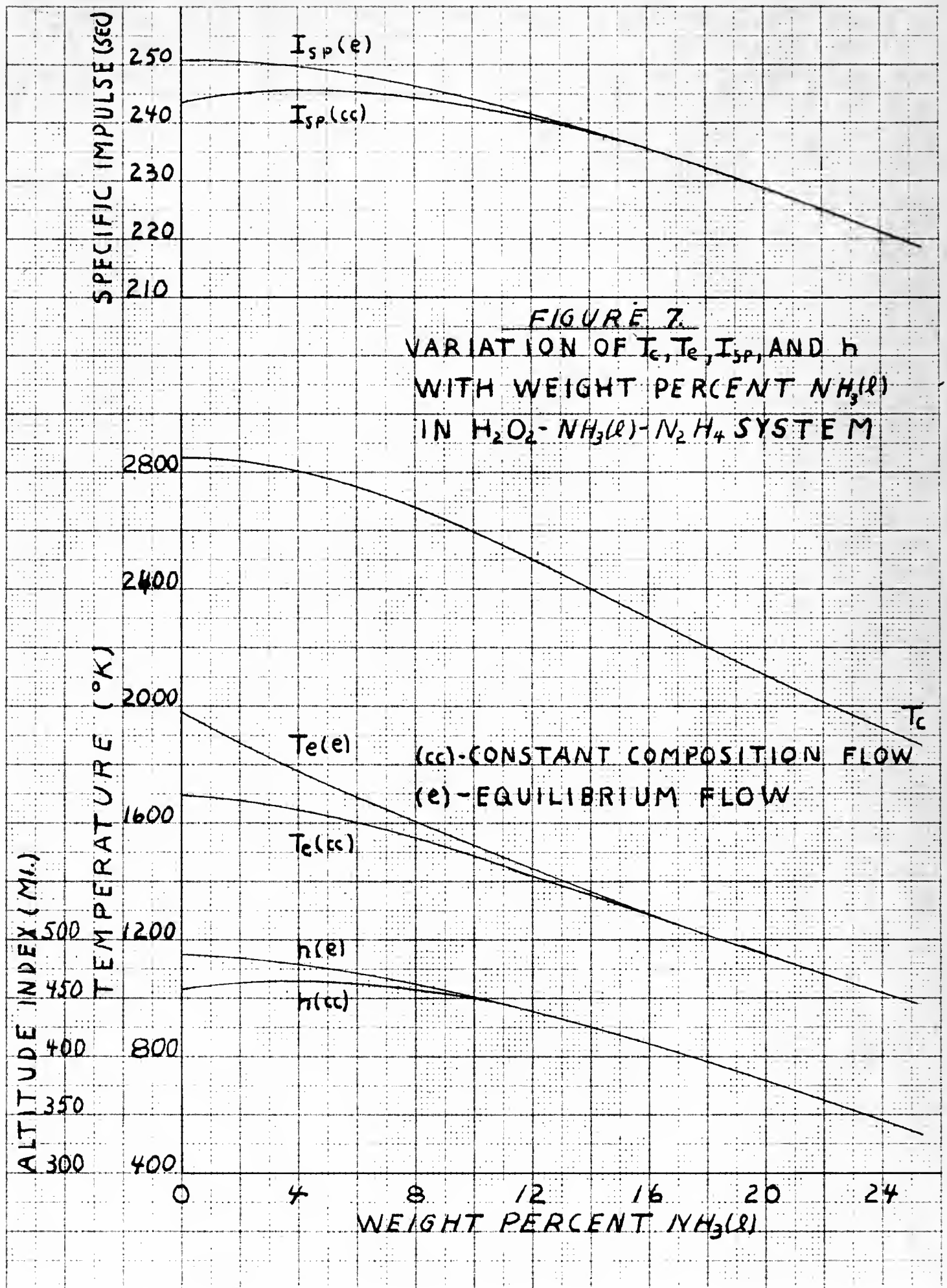
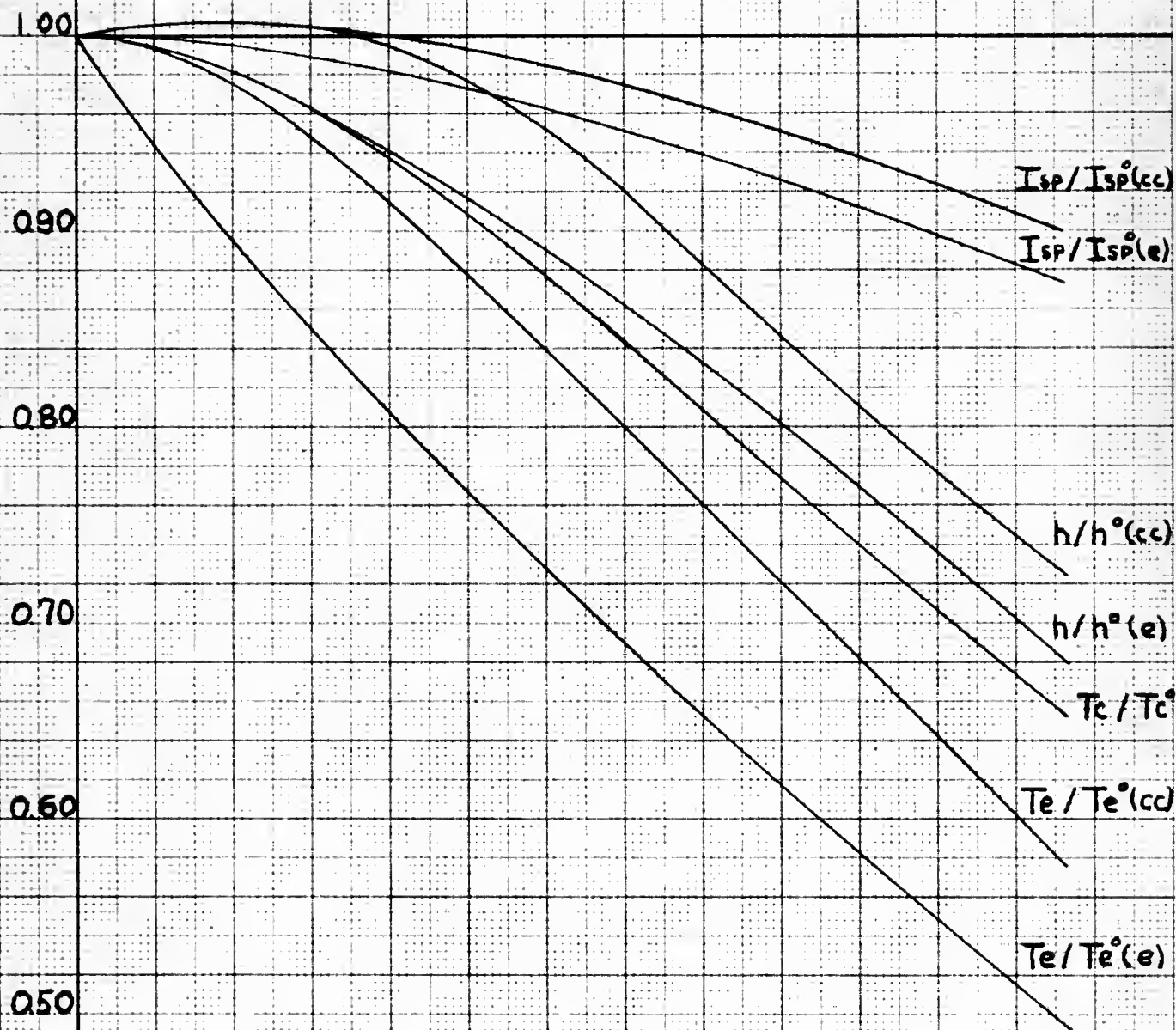


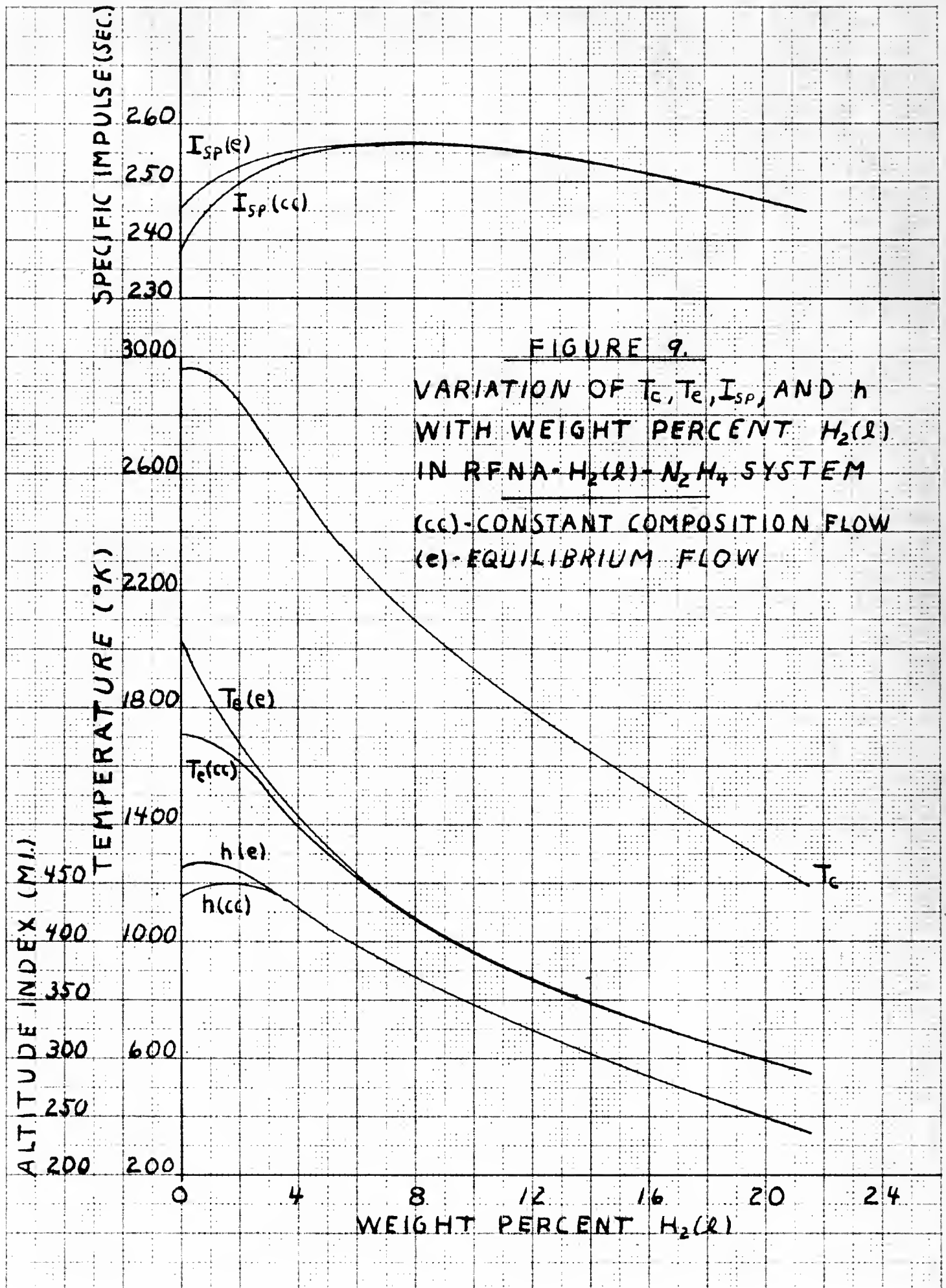
FIGURE B  
VARIATION OF  $T_c/T_c^\circ$ ,  $T_e/T_e^\circ$ ,  $I_{sp}/I_{sp}^\circ$ ,  
AND  $h/h^\circ$  WITH WEIGHT PERCENT  
 $NH_3(l)$  IN  $H_2O_2-NH_3(l)-N_2H_4$  SYSTEM

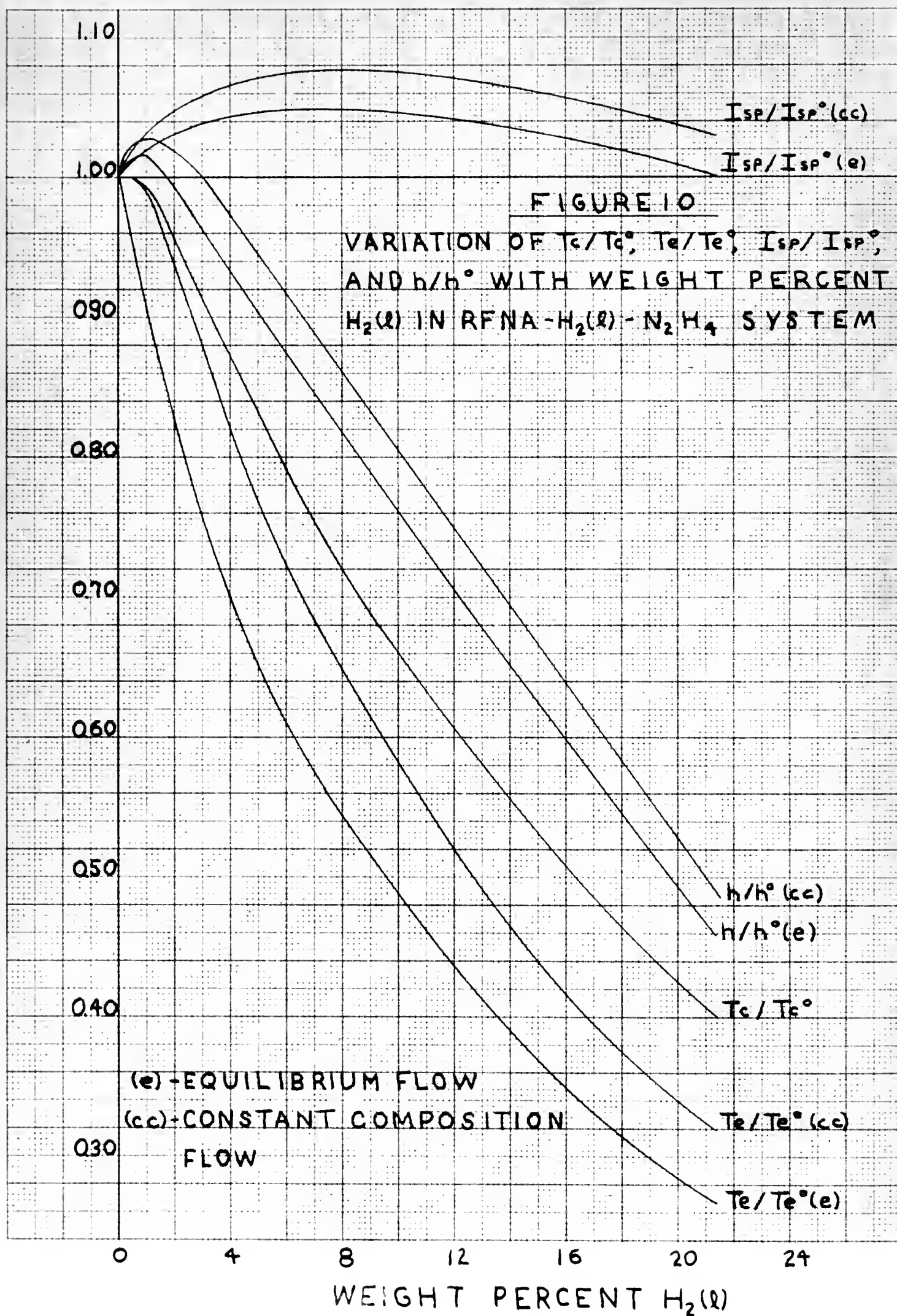


(e) - EQUILIBRIUM FLOW

(cc) - CONSTANT COMPOSITION FLOW







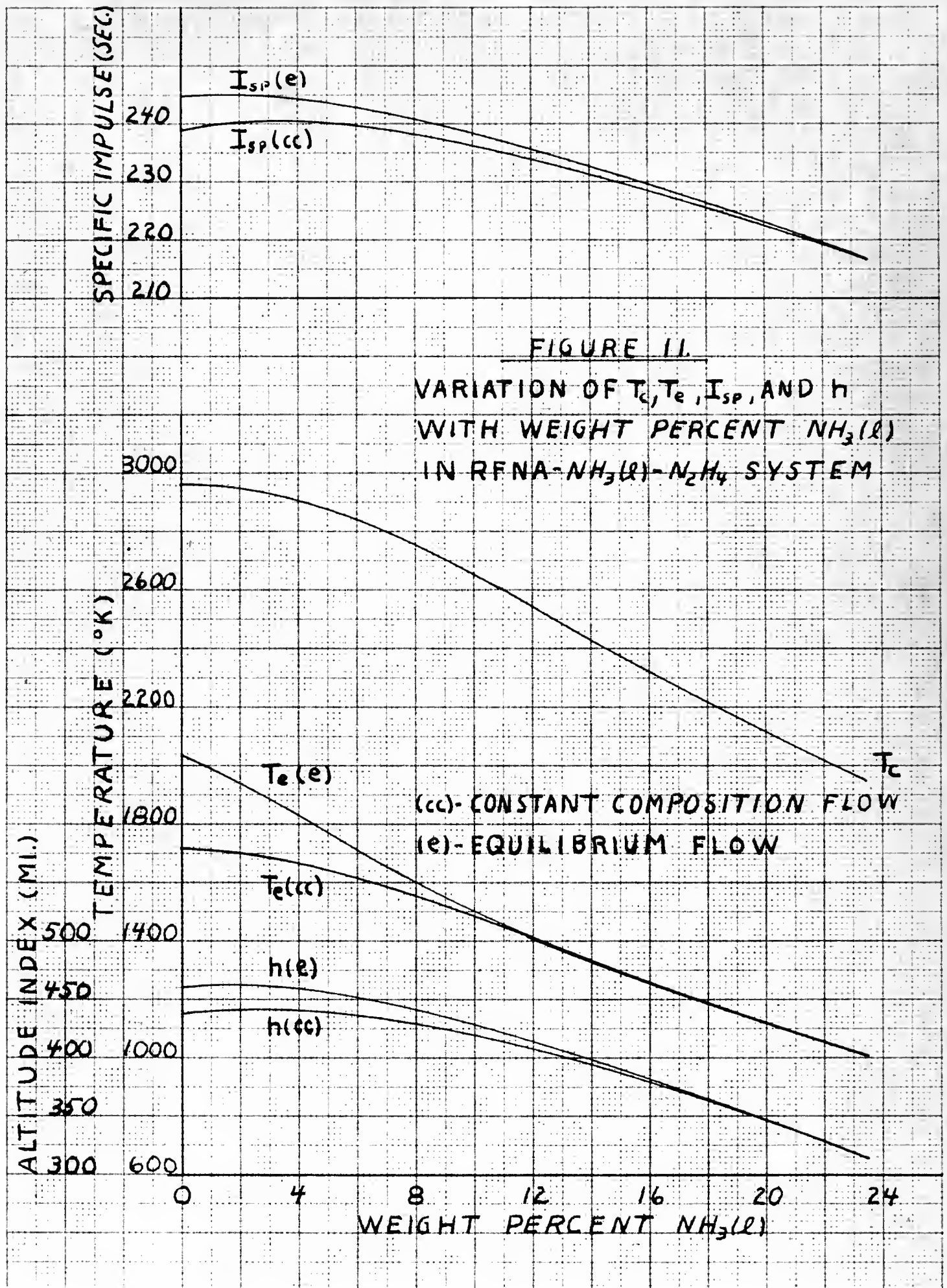
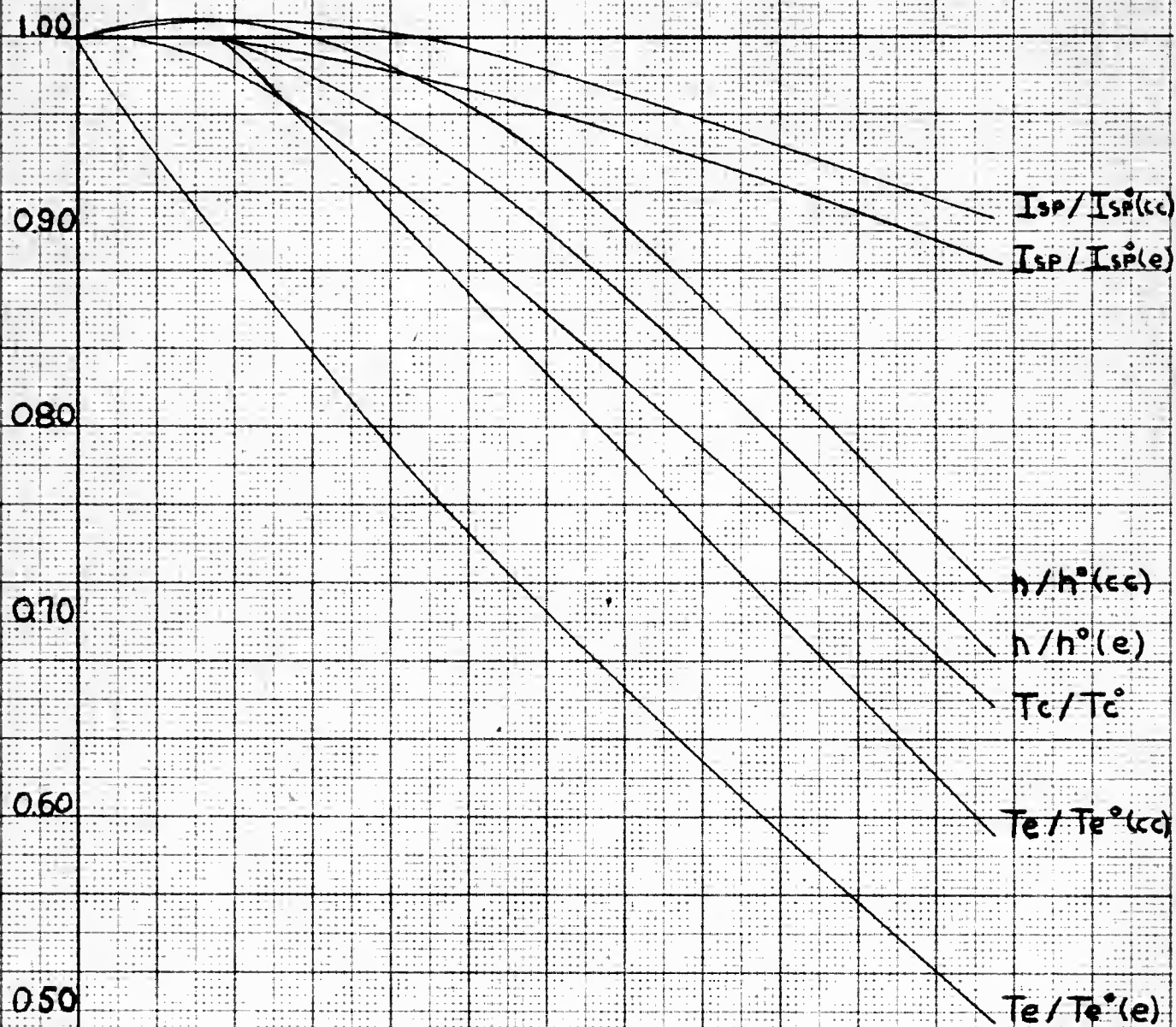


FIGURE 12

VARIATION OF  $T_c/T_c^\circ$ ,  $T_e/T_e^\circ$ ,  $I_{SP}/I_{SP}^\circ$ ,  
AND  $h/h^\circ$  WITH WEIGHT PERCENT  
 $NH_3(l)$  IN RFNA- $NH_3(l)$ - $N_2H_4$  SYSTEM



(e) - EQUILIBRIUM FLOW

(cc) - CONSTANT COMPOSITION FLOW

0.40

WEIGHT PERCENT  $NH_3(l)$



FIGURE 13

VARIATION OF  $T_c/T_c^\circ$  WITH WEIGHT  
PERCENT THIRD COMPONENT

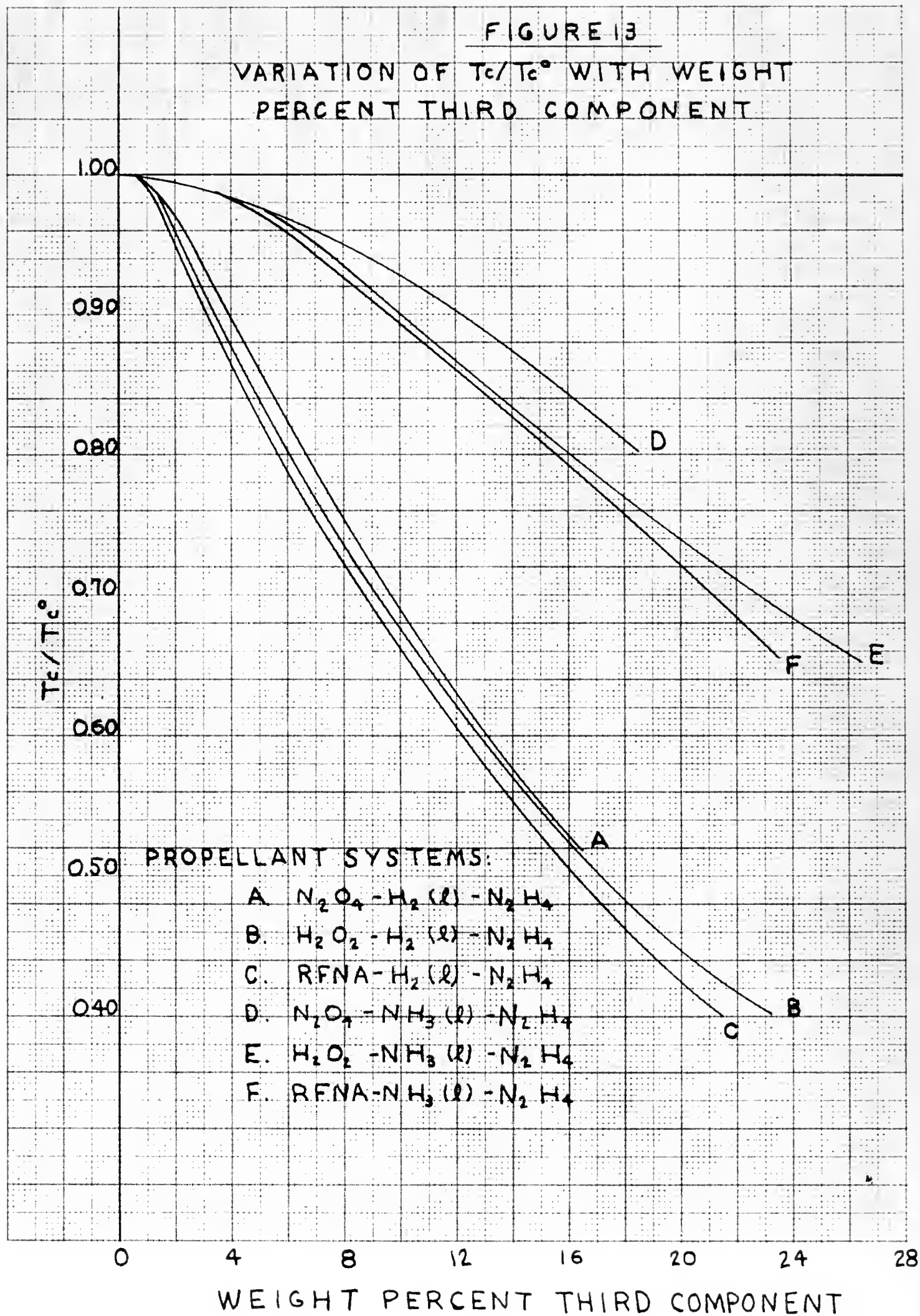


FIGURE 14

VARIATION OF  $I_{SP}/I_{SP}^0$  WITH WEIGHT PERCENT THIRD COMPONENT

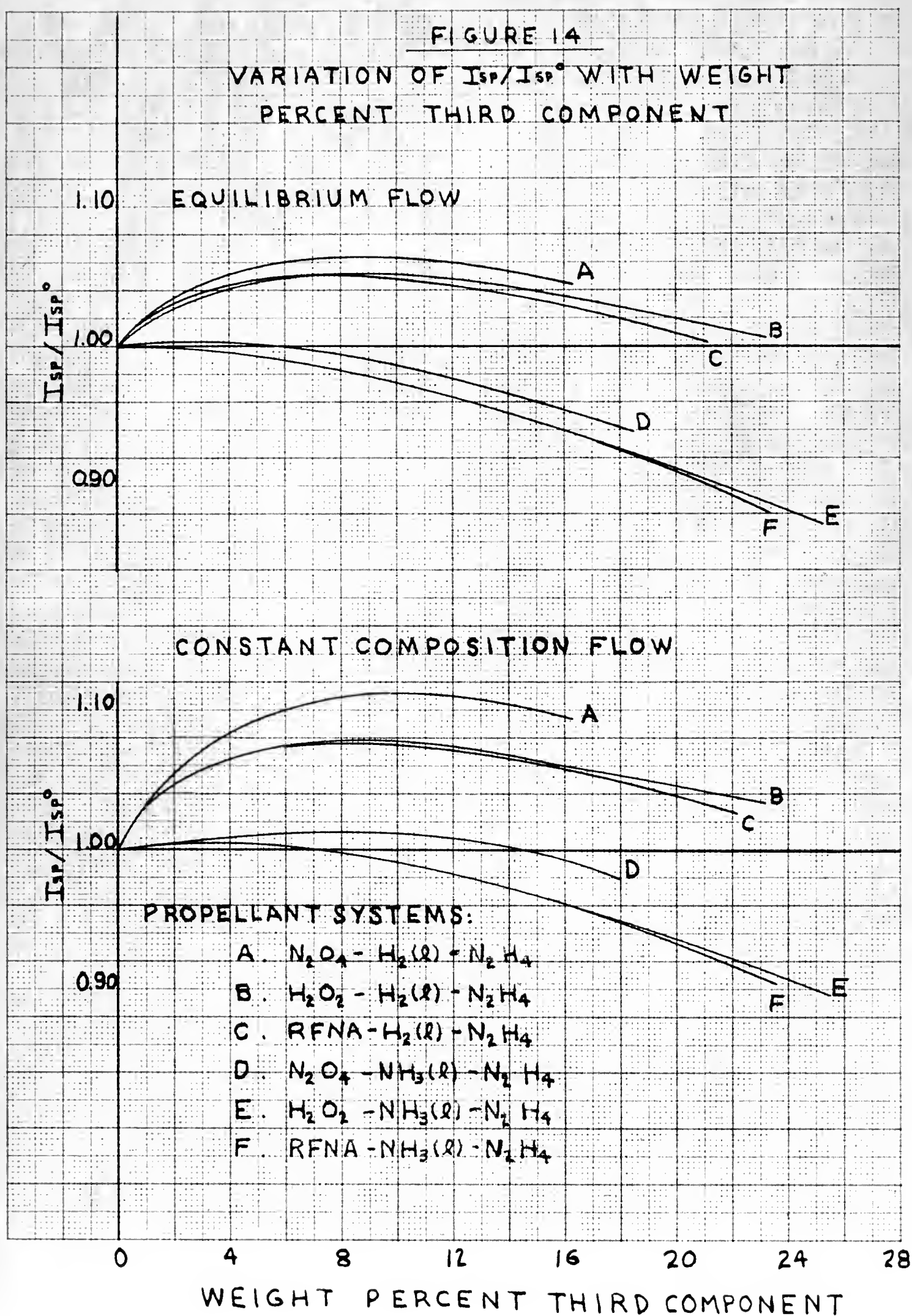


FIGURE 15.  
VARIATION OF  $h/h^0$  WITH WEIGHT  
PERCENT THIRD COMPONENT  
FOR EQUILIBRIUM FLOW

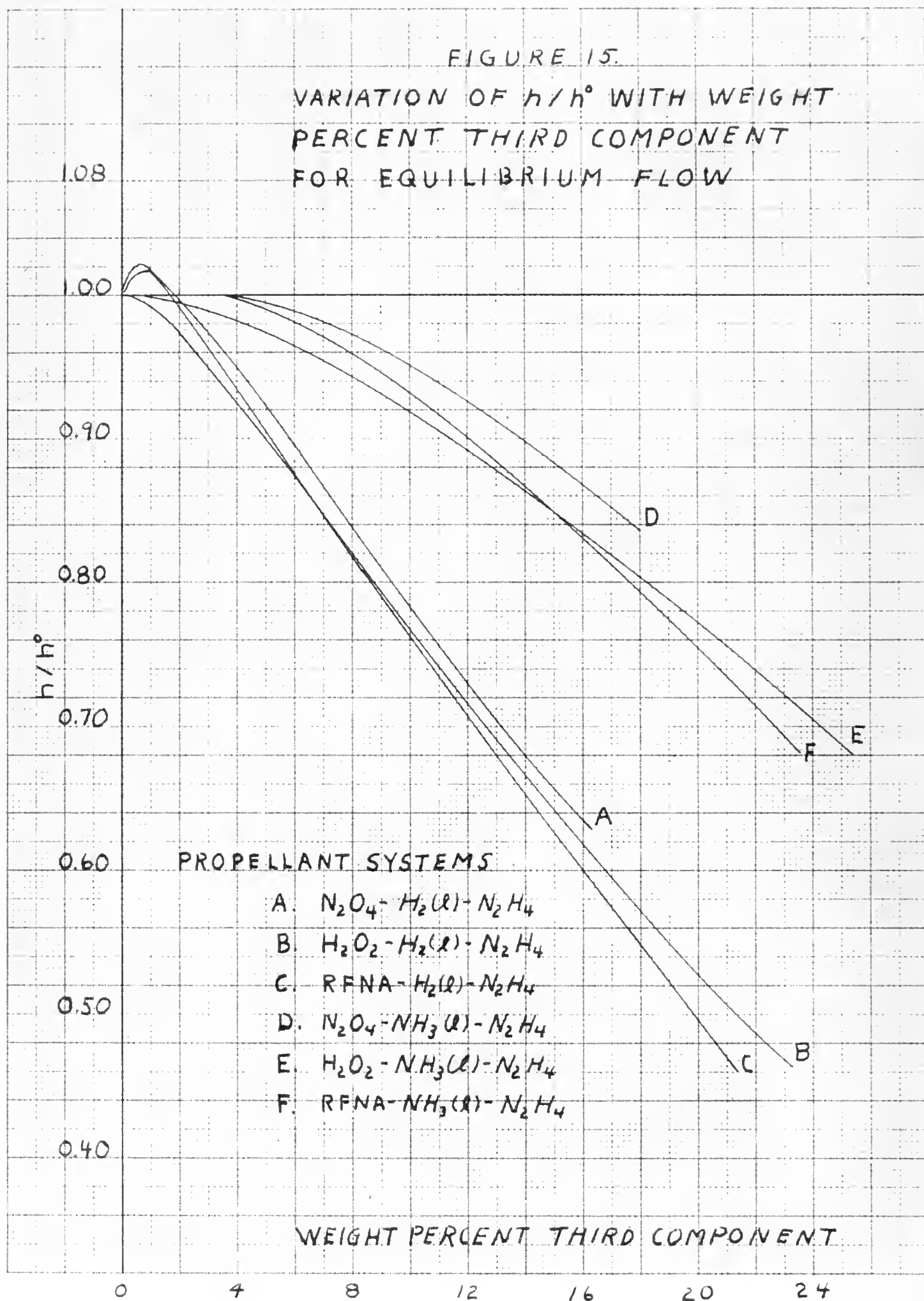




FIGURE 16  
 VARIATION OF  $h/h^*$  WITH WEIGHT  
 PERCENT THIRD COMPONENT  
 FOR CONSTANT COMPOSITION FLOW

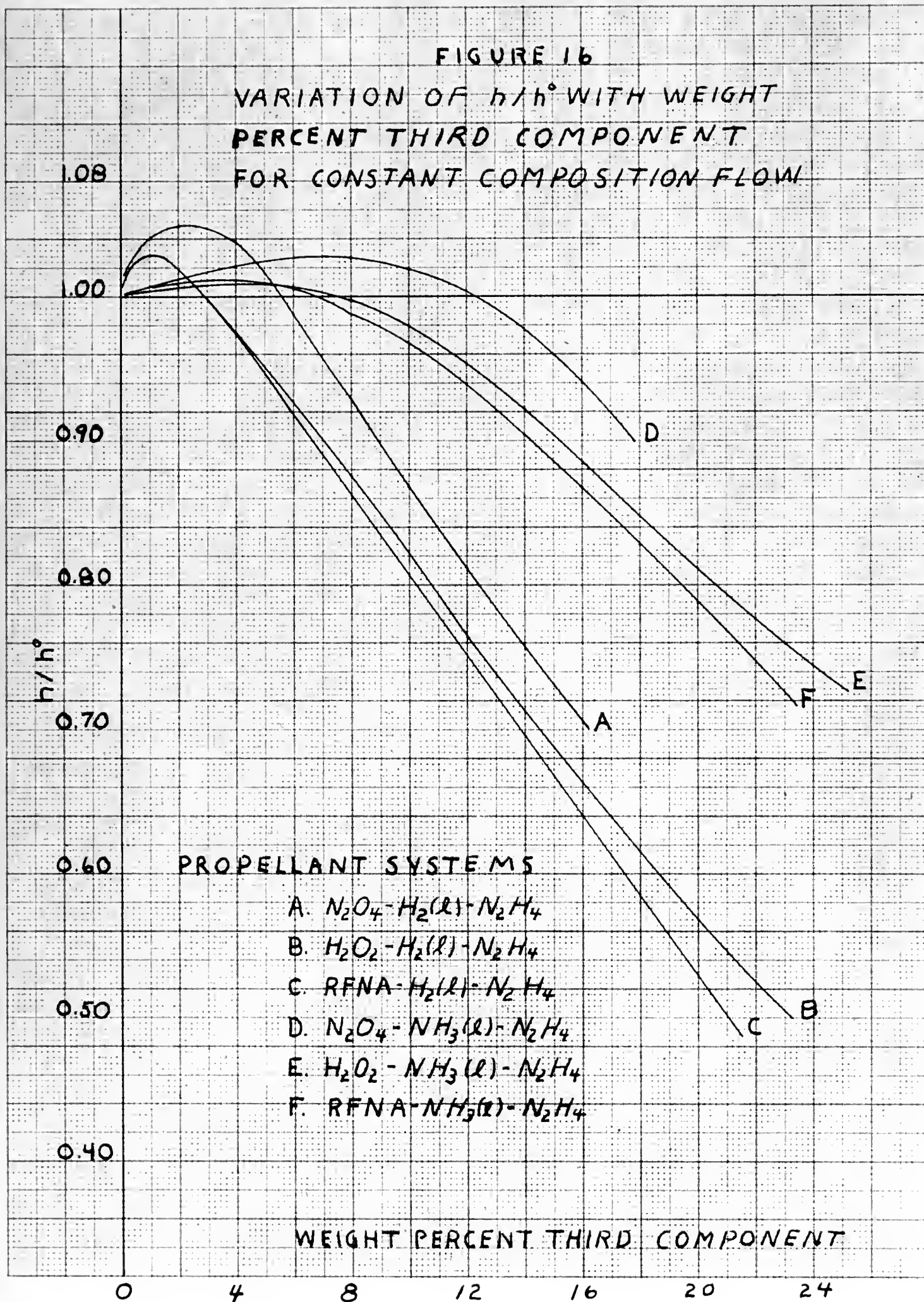
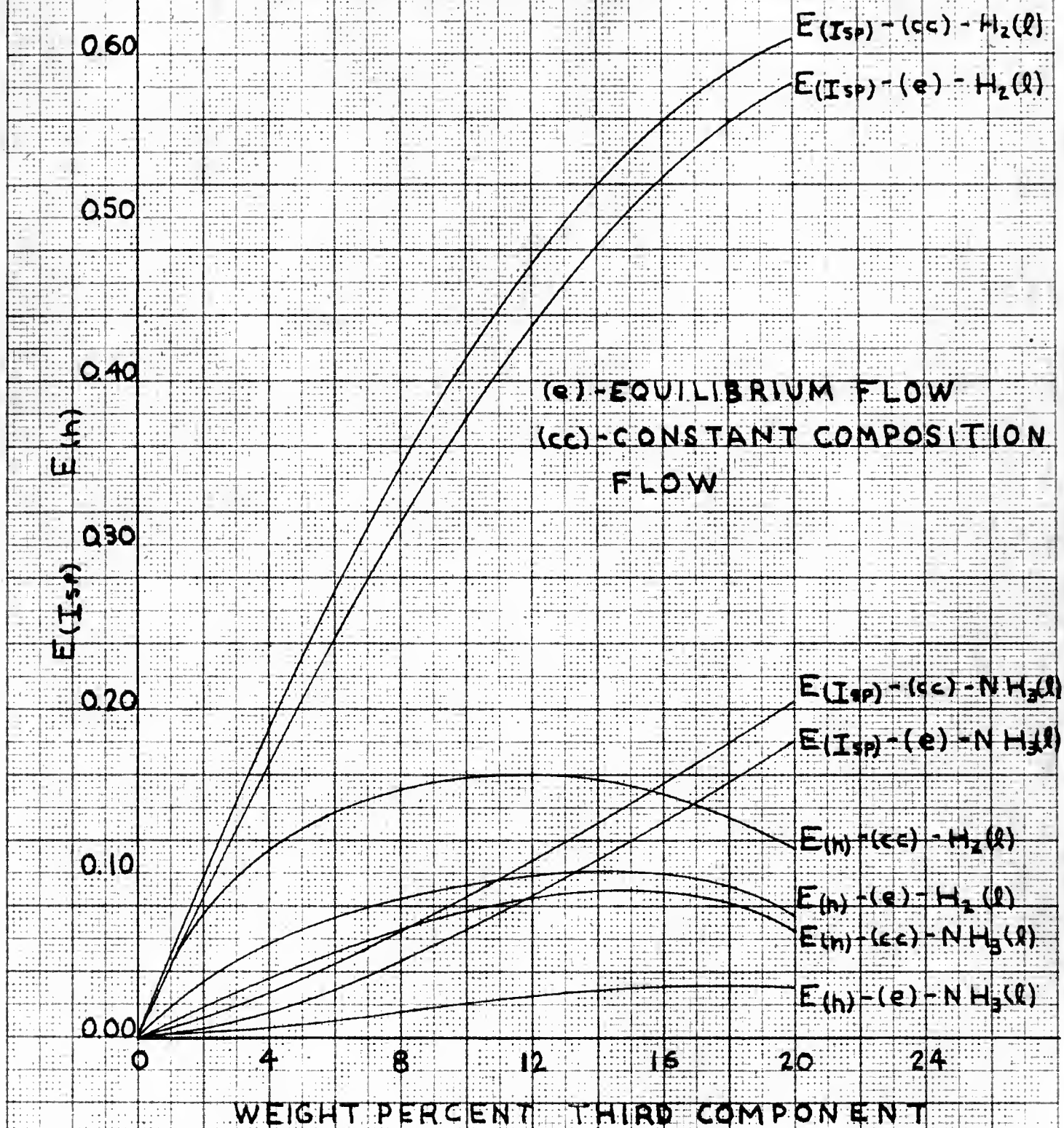


FIGURE 17

VARIATION OF  $E(I_{sp})$  AND  $E(h)$  WITH  
WEIGHT PERCENT THIRD COMPONENT



[illegible]

Thesis

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Sims

Performance calculations of rocket tri-propellant systems.

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